Volume XXVI. *April, 1908.* *Number 4.*

THE

PHYSICAL REVIEW.

SOME STUDIES ON THE CHANGE OF ELECTRICAL RESISTANCE OF SELENIUM CELLS.

By F. C. Brown and Joel Stebbins.

THIS paper deals with the effect of various agencies on the resistance of selenium cells. It has been found convenient to divide it into the following sections.

I. The Effect of Pressure on the Resistance.
II. The Light Sensitiveness at Different Pressures.
III. The Effect of Temperature on the Resistance.
IV. The Light Sensitiveness at Different Temperatures.
V. The Effect of Hydrogen Peroxide on the Resistance.
VI. The Effects of Radium.
VII. Discussion of Results.
VIII. Summary.

The selenium cells used in these experiments were of three kinds, those made by Ruhmer, by Giltay, and by ourselves. When exposed to light the Ruhmer cells increased in conductivity as much as twenty times, those made by Giltay as much as seventy times, and some of our own make about nine times. However we remade one of the Giltay cells and it then had a sensitiveness of 55 to 1. We do not known how the Ruhmer or the Giltay cells were made. In general we used the method of making outlined by Bidwell[1] although we sometimes crystallized the selenium at a higher temperature than that given by him.

[1] Phil. Mag., ser. V., Vol. 3, p. 351.

THE EFFECT OF PRESSURE ON THE RESISTANCE.

The effect of pressure alone on the selenium cells was studied in three ways, first by liquid pressures from a Cailletet pump, second by using air pressures obtained by a Norwalk four-stage compressor, third by using liquid pressures which were maintained by air pressure. A preliminary report on the experiments made by the first method was given to the American Physical Society, February, 1904.[1]

In the first method kerosene was placed in the piezometer. Pressure was obtained by pumping water into the piezometer with the Cailletet pump. The water went to the bottom of the piezometer and did not affect the insulation resistance of the selenium cell.

In order to get an idea of the temperature change due to compression of the kerosene a coil of no. 40 silk-covered copper wire was placed in the piezometer which was kept fairly constant in tap water at 13.4° C. The coil had a resistance of 39.51 ohms at 13.4° C. After the resistance of the coil had become constant it was assumed that the temperature of the kerosene was the same as that of the tap water. Then the pressure was raised to 425

$\frac{\text{kgm}}{\text{cm}^2}$	Ohms Resistance.	Time.	Temperature.
1	39.51	8 : 20	13.4° C.
425	40.11	8 : 25	
420	39.95	8 : 27	
420	39.84	8 : 29	
420	39.74	8 : 30	
420	39.64	8 : 32	
420	39.61	8 : 34	
420	39.55	8 : 39	
420	39.54	8 : 40	
420	39.53	8 : 43	
420	39.52	8 : 48	
420	39.51	8 : 54	
420	39.51	8 : 54½	
1	38.91	8 : 55	
1	39.06	8 : 57	
1	39.21	8 : 58	
1	39.31	9 : 00	
1	39.40	9 : 03	
1	39.46	9 : 06	
1	39.48	9 : 08	

[1] PHYS. REV., March, 1904.

kgm./cm². and maintained at 420 kgm./cm². until the coil had returned to the resistance that it had previously at atmospheric pressure. Then the pressure was suddenly lowered to atmospheric pressure and the kerosene was thereby cooled the same amount it had been heated previously by the compression. The resistance was measured at the intervals shown in the table above.

These observations show conclusively as is readily seen from Fig. 1, that the change of resistance in the copper coil is mainly

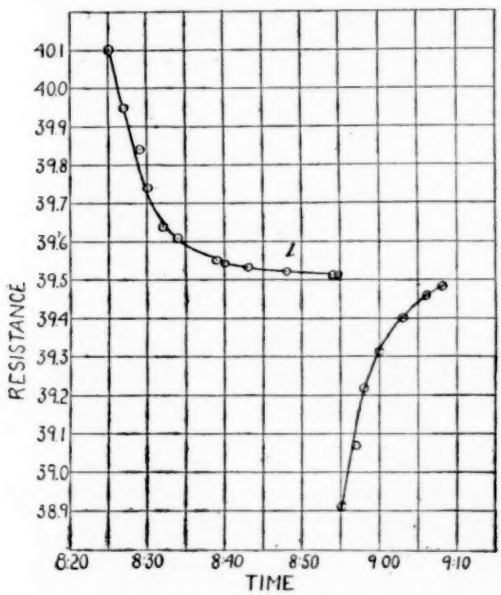

Fig. 1.

if not entirely due to temperature change. For when the kerosene is compressed and heated it returns to the temperature of the tap water and at about the same rate as that when the kerosene is cooled by letting the pressure off. We see that in thirty minutes the kerosene has returned to the temperature of the tap water when the pressure was suddenly raised or lowered 420 kgm./cm². It is to be noted that the resistance changed the same amount and oppositely when the pressure was lowered as when it was raised. Roughly one ohm change of resistance signifies seven degrees change of temperature. After 20 minutes the coil had returned

within .2 degree and in 10 minutes it had returned to within one degree. This was when the change of pressure was 420 kgm./cm². and when the coil was in a hard rubber case. If the pressure change were less the temperature change would be correspondingly less.

In all cases some modification of the Wheatstone's bridge method was employed to measure the resistance.

The following are some of the first observations with selenium cells under pressure. One of our own cells no. 4*a* was used. The piezometer was kept in tap water at 14.8 to 16.° C.

E.M.F. in Circuit Volts.	Pressure, kgm/cm².	Resistance, Ohms.
1.4	450	650,000
	270	1,300,000
	350	1,100,000
	320	1,200,000 after 10 minutes
	220	1,440,000 " 40 "
	185	1,530,000
	180	1,700,000
	160	1,720,000
	80	1,730,000
	20	1,920,000
	22	1,940,000
	1	1,990,000 after 10 minutes
10.0	1	1,170,000
	240	900,000
	400	770,000
	495	720,000
	450	770,000
	70	1,120,000
	72	1,100,000
	1	1,230,000
	1	1,200,000 after 10 minutes

These data are shown in curves 2 and 3 (Fig. 2). When 1.4 volts are used in the circuit, the average change of resistance per atmosphere is 2,200 ohms. When 10 volts are used the change of resistance is about 1,100 ohms per atmosphere. In the first case the percentage change is .11. In the second case it is .05.

Again readings were taken for cell 5 under pressure. The piezometer was packed in ice and the temperature of the room was 10° C. The electromotive force in the circuit was 1.4 volts. These

data are shown graphically in Fig. 3. The mean percentage change per atmosphere is .12.

Similiar results were obtained with other cells. One cell no. 6 with platinum electrodes had a resistance at atmospheric pressure

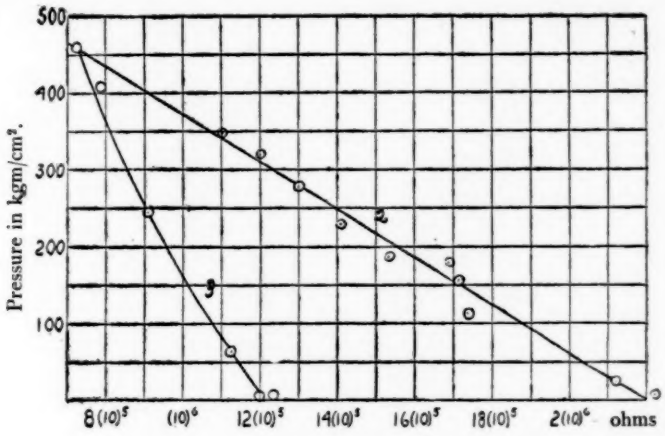

Fig. 2.

of 1,670,000 ohms. Its average decrease per atmosphere was .11 per cent. To compare these three cells, one having round copper electrodes, one with flat copper electrodes and one with platinum

Time.	Pressure, kgm/cm².	Resistance, Ohms.	Change of Resistance per Atmosphere.
2 : 52 P. M.	490	44,600	144
2 : 54	496	44,600	
2 : 57	570		
2 : 59	490	42,400	147
3 : 15	490	48,700	
3 : 20	478	49,700	
3 : 38	453	51,700	139
3 : 45	440	53,100	140
4 : 15	405	56,000	
4 : 25	333	64,300	
4 : 30	250	74,600	156
4 : 35	208	81,900	160
4 : 39	150	90,500	
4 : 44	102	99,900	138
4 : 47	59	106,900	
5 : 18	1	115,000 112,000	

electrodes, when 1.4 volts were used in the circuit, the change of resistance was .11 per cent., .12 per cent. and .11 per cent. respectively.

The conductivity of these cells was about doubled when they were exposed to strong light. However they were made at dif-

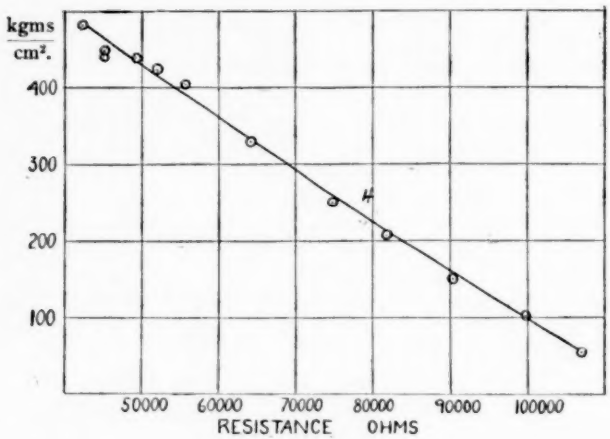

Fig. 3.

ferent times and had electrodes of different shape and material, and the initial resistance is seen to vary more than ten times. It would seem that for selenium cells of a given light sensibility and with con-

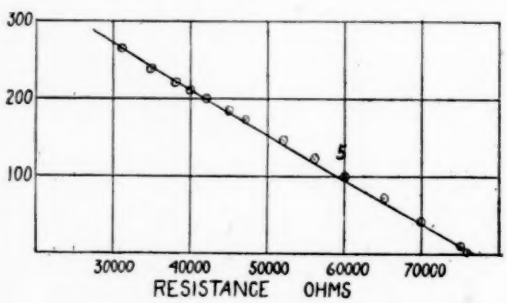

Fig. 4.

stant voltage in the circuit, that the percentage change of resistance per atmosphere is constant.

In Fig. 4 is shown the resistance of Ruhmer selenium cell no. 454 with varying liquid pressures. Three volts were used in the circuit. The sensibility of this cell was about 10 to 1. It is seen that the percentage decrease of resistance for one atmosphere is .23.

In studying air pressures the selenium cells were placed is a piezometer made of car axle steel. The piezometer was connected in series with a steel tank of about 15 cubic feet capacity. The tank was so fitted with valves that the pressure could be let off the piezometer without lowering the pressure in this supply tank. The pressure was furnished by a Norwalk four-stage compressor. About a month before this work was begun with selenium the compressor and tank were used in connection with the liquid-air plant. Lime and potassium hydrate were used as purifiers in the plant. In the first few experiments the air used for pressure was drawn through lime.

Giltay cell no. 92 was the first to be studied in air pressure. On May 20, at atmospheric pressure and about 23° C., the resistance was 1,300,000 ohms in the dark. When 1,400 pounds pressure was applied, the resistance first fell to about 1,200,000, but it kept on decreasing and after about two hours it had reached 520,000 ohms with the pressure on. When the pressure was taken off the resistance recovered immediately to 590,000 ohms.

The condition of the cell afterwards was as follows:

May 22, 1,100,000 to 1,000,000 ohms.
May 23, 14,300 ohms after being under 400 pounds pressure 12 hours.
May 23, 14,400 ohms at atmospheric pressure.
May 24, 7,100 ohms.
May 27, 10,500 ohms.
July 15, 10,300 ohms.

On the last date the selenium was remelted and recrystallized. Its resistance was as follows:

10,300	ohms at	27° C.	
6,000	"	150 "	
1,700	"	204 "	
770	"	209 "	
770	"	213 "	
20,000	"	150 "	
80	"	219 "	
∞	"	218 "	selenium melted.
6,400	"	155 "	
1,900	"	200 "	
4,000	"	183 "	
2,700,000	"	25 "	
50,000	"	25 "	10 cm. from 16 c.p. light.
2,600,000	"	25 "	in dark again.

It is evident from the above table that the resistance of the cell decreased still further as the temperature was raised.

We then tried four cells of our own make under air pressure, and every one behaved just as the Giltay cell did. After being under air pressure from one to twenty hours the resistance reached a final value from which the cells did not recover.

Next the piezometer was filled with kerosene and the pressure was maintained by the air pressure bearing on the surface of the liquid. Several cells were tried and there was no permanent break-

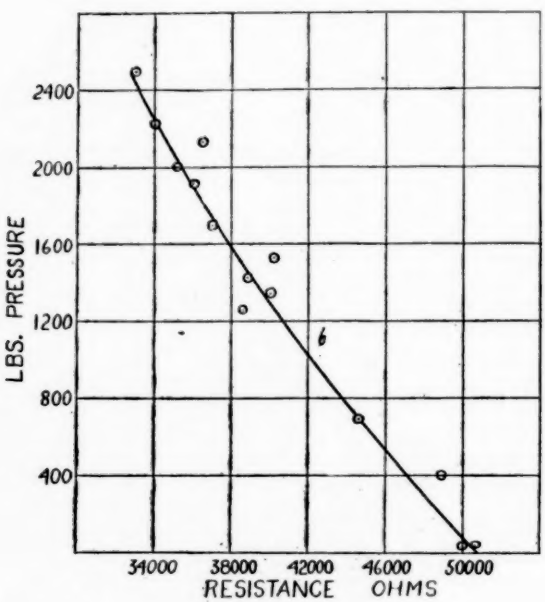

Fig. 5.

ing down of the resistance in any case. When the pressure was raised or lowered the cell changed its resistance almost instantly.

Afterwards these cells which had been tested under liquid pressure were washed in benzene and again placed in air pressure. The resistance then showed no signs of breaking down. In curve 6 (Fig. 5) it is seen how the resistance of the cell varied as the pressure was run up and down again. The pressure was left on more than a day. The sensibility of cell no. 23 was about 8 to 1. The mean

percentage decrease of resistance per atmosphere is seen to be about .22.

We are not prepared to say why the first cells broke down in resistance under air pressure and the last ones did not. There may have been something in the pressure system which was blown out before the last set of observations were taken. The benzene or oil may have prevented the action of the air in the cases in which the resistance did not break down. We do not think the structure of the cells was different in the two cases.

The Light Sensitiveness at Different Pressures.

The selenium cell used in these experiments was the Giltay no. 92 after it had been remelted and reannealed. It was fixed in a hard rubber mounting so that it could be easily and rigidly fastened to electrical connections entering from the side of the piezometer.

The piezometer was made from car axle steel. It was provided with electrical connections similar to some described by Knipp.[1] Opposite one of the electrical connections was an opening to the pressure tank. Opposite the other was a plate-glass window to allow the entrance of light to the cell.

After having considerable difficulty with air pressure around the cell it was decided to use liquid pressure. The piezometer was nearly filled with kerosene, which not only protected the cell from breaking down but also diminished the errors due to temperature. The fact that it absorbed considerable light did not lessen the accuracy of the results.

At first the cell was illuminated by an amyl-acetate standard candle but it was difficult to keep the candle adjusted. The results here published were obtained when an incandescent light giving about 1 c.p. was placed at a distance of 15 cm. from the cell. The time of exposure was 10 seconds. It was regulated by a knife switch placed in the circuit. The light was run by a storage battery giving 6.21 volts during the experiments.

The change of resistance was measured by placing the cell in one arm of a Wheatstone's bridge. A Leeds and Northrup Type H, aperiodic galvanometer was used. The deflection given when the cell was illuminated was taken as indicative of the change of

[1] Phys. Rev., XI., 129.

resistance. This change was found directly by finding what known change of resistance would produce the same deflection. The period of the galvanometer, 3 seconds, and the time of exposure, 10 seconds, were such that no appreciable error entered in the final results. Longer exposures would have been used had it not been that the time for recovery of the light sensitiveness would have increased. Before beginning a series of observations the cell was exposed to the incandescent light for a minute. Then after three-minute intervals the cell was exposed for 10 seconds and the readings were taken. Using constant time intervals insured the same stage of recovery. The same error entered with the pressure on as with the pressure off.

The sensitiveness was compared at pressures varying from 15 pounds to 2,500 pounds. Following is a sample of the series of readings taken. The electromotive force in the Wheatstone's bridge circuit was 11.9 volts.

Time.	Resistance of Selenium Cell.	Readings.		Deflection in mm.	Ohms Change of Resistance.	Percentage Change.	Pressure, Lbs.
3 : 21		− 3.0	27.0	30.0			
3 : 24		15.6	44.6	29.0			
3 : 27		23.4	52.4	29.0			
	2,400,000			29.3	225,000	9.38	15
3 : 30		−19.7	13.5	33.2			
3 : 33		−35.3	− 1.5	33.8			
3 : 36		−39.8	− 6.0	33.8			
	1,860,000			33.6	159,000	8.55	1,970
3 : 39		−20.0	8.7	28.7			
3 : 42		0.8	29.7	28.9			
3 : 45		12.0	40.8	28.8			
	2,520,000			28.8	241,000	9.56	15
3 : 48		−13.5	18.0	31.5			
3 : 51		−36.6	− 4.0	32.6			
3 : 54		−45.6	−13.3	32.3			
	1,970,000			32.1	170,000	8.63	1,890
3 : 58		−33.4	− 4.3	29.1			
4 : 01		−12.4	16.5	28.9			
4 : 04		− 0.3	28.2	28.5			
	2,660,000			28.8	270,000	10.15	15

SUMMARY OF RESULTS ON LIGHT SENSITIVENESS AT VARIOUS PRESSURES.

Series.		I.	II.	III.	IV.
Mean resistance of selenium cell, ohms.	pressure on	2,607,000	2,270,000	2,133,000	1,915,000
	pressure off	2,850,000	2,878,000	2,435,000	2,530,000
Mean pressure, lbs.		730	2,075	525	1,930
Change of resistance due to light action.	pressure on	185,000	131,000	149,000	164,000
	pressure off	220,000	200,000	178,000	245,000
Percentage change of resistance due to light.	pressure on	7.11	5.77	6.99	8.59
	pressure off	7.70	6.92	7.32	9.70
Change of light effect due to pressure.		0.59	1.15	0.33	1.11
Change of light effect per lb. pressure.		.00083	.00056	.00065	.00058

Area of cell exposed, from .3 to .4 sq. cm.

From the preceding data we get a small but measurable variation in the light sensitiveness at different pressures. For the percentage change of resistance per pound of pressure, the lowest value is .00056 and the highest is .00083. This variation in the different series may have been produced by different temperatures, or by having different areas exposed to the light. However the variation in the candle power of the light may be considered zero. Also the error due to time of exposure was practically zero.

Probably the greatest source of error was due to temperature variation. When the air pressure was turned on from the large supply tank, there was some heating effect in the cell due to the compression of the kerosene. The air in contact with the kerosene probably did not have any immediate effect on the temperature of the cell. In order to approximate the temperature change when the air was turned on, a copper coil was placed in the piezometer. Its resistance was 44.05 ohms at 27.5° C. at atmospheric pressure. One minute after 1,500 lbs. pressure was applied the resistance was 44.20 ohms. After two minutes 44.07 ohms and four minutes 44.06. In five minutes then the temperature had practically returned to its original value.

During the experiments the temperature of the piezometer varied between 24° and 27.5° C., and it was estimated that the cell did not vary more than this. The variation from 6.92 to 9.70 per cent. in the different series may have been partly due to temperature. It was more probably caused by slight differences in the adjustment of the selenium cell and its position with respect to the light.

The Effect of Temperature on the Resistance.

The effect of temperature on the resistance of the selenium cell is shown in curves 7, 8 and 9 (Figs. 6, 7, 8), for the temperatures

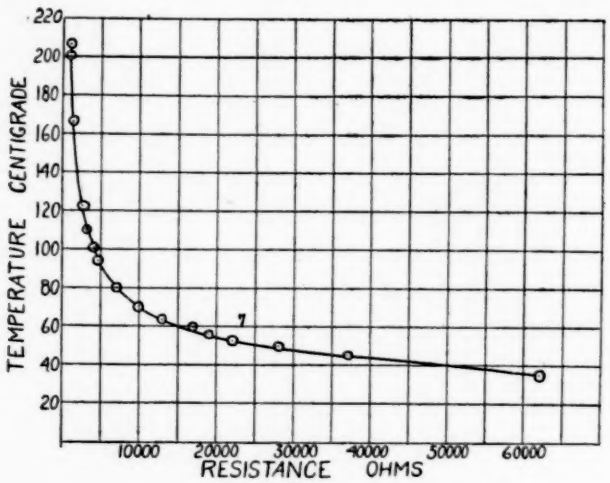

Fig. 6.

indicated. Two points are to be noted, the amount of variation with temperature and the similarity of the variation in the three cells. If the percentage change of resistance were plotted against temper-

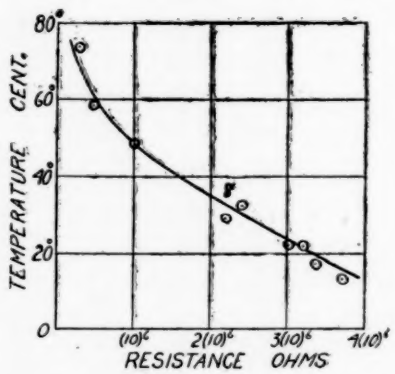

Fig. 7.

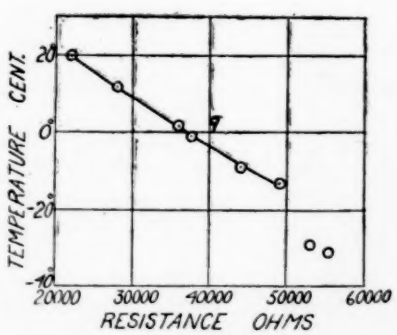

Fig. 8.

ature, the last point would be more readily seen. It was impossible to get the resistance of the cell at liquid-air temperatures because of the cracking of the selenium.

Evidently it would be more satisfactory if we could determine the effects on selenium in terms of specific resistance, but this cannot be done accurately because of the variable amount of selenium in a cell and the structure of the cell.

Light Sensitiveness at Different Temperatures.

To determine the sensitiveness at different temperatures, the Giltay no. 92 was connected in one arm of the Wheatstone's bridge. The cell was placed in a kerosene bath surrounded by a water-bath. About 1 sq. cm. area of the cell was exposed to an incandescent light, of about 1 c.p., and at a distance of 15 cm. About one fifteenth of the total area of the cell was illuminated. The cell was illuminated by light passing above the surface of the water-bath. The thickness of kerosene passed through was not much different from that passed through by the light in the pressure-light experi-

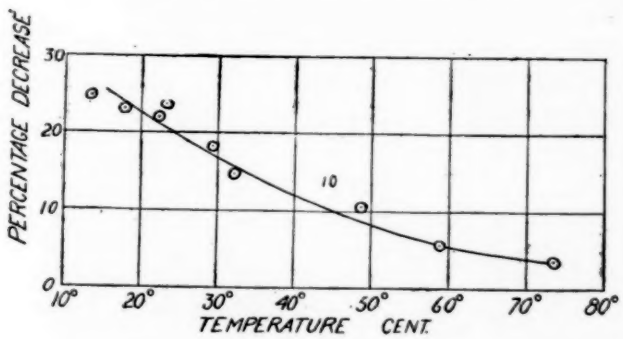

Fig. 9.

ments. The current for the light was obtained from 3 storage batteries giving 6.21 volts. The time of exposure (10 seconds) was regulated by a knife switch. When the cell was exposed there was a deflection of the galvanometer in the manner explained in a previous section and the change of resistance was calculated.

The temperature of the cell was regulated by the surrounding water-bath, which was heated with a bunsen burner or cooled with ice shavings. It will be noticed from the following data that these results are taken as nearly as possible under the conditions prevailing in the study of light sensitiveness at different pressures.

These data are shown graphically in curves 10 and 11 (Figs. 9, 10). In curve 11 we have the sensitiveness expressed for different values of the resistance of the cell, this resistance being a function of the temperature. This resistance is also a function of the state of recovery of the cell and other conditions. But the sensitiveness is probably a function of all these conditions. Consequently

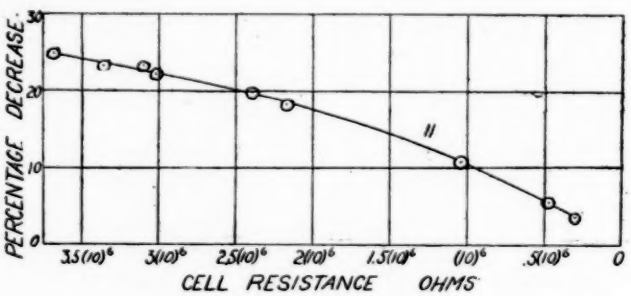

Fig. 10.

we should expect more concordant results in curve 11, since the experiments were made on different days when the state of recovery was different.

THE EFFECT OF HYDROGEN PEROXIDE ON THE RESISTANCE.

We wish to give here some of our own meager observations on the effect of hydrogen peroxide in order to make comparisons with other phenomena.

A cell having a resistance of 80,000 ohms decreased to 50,000 ohms when placed 5 cm. above a surface of hydrogen peroxide. But when the surface of the hydrogen peroxide was enveloped by a sheet of lead, copper, aluminium or even paper there was no appreciable change in the resistance from 80,000 ohms. However, if any of these sheets did not completely cover the surface of the liquid, merely shutting off all the straight line paths from the surface of the hydrogen peroxide to the selenium cell, then the change of resistance was almost as marked as in the first case. When a cell decreased in resistance owing to neighboring hydrogen peroxide, its recovery seemed to be slower than recovery from light,

LIGHT SENSITIVENESS AT DIFFERENT TEMPERATURES.

Time.	Temperature, Centigrade.	Resistance of Cell in Ohms.	Readings.		Deflection, mm.	Change of Resistance.	Percentage Change of Resistance
1 : 54 P. M			− 1.8	62.5	64.3		
1 : 57			− 4.0	60.3	64.3		
1 : 60			− 4.0	59.8	63.8		
2 : 03			− 4.2	59.3	63.5		
	22.3°	3,045,000			64.0	670,000	22.0
2 : 39			8.0	69.2	61.2		
2 : 42			0.4	62.5	62.1		
2 : 45			− 0.2	62.0	62.2		
2 : 48			− 0.2	62.1	62.3		
	17.9	3,370,000			62.0	780,000	23.1
3 : 25			2.0	63.4	61.4		
3 : 28			− 0.8	61.0	61.8		
3 : 31			− 0.8	60.4	61.2		
3 : 34			− 0.8	60.4	61.2		
	13.2	3,725,000			61.4	927,000	24.9
4 : 15			− 5.9	63.5	69.4		
4 : 18			− 10.0	59.9	69.9		
4 : 21			− 13.0	56.6	69.6		
4 : 24			− 15.7	53.0	68.7		
	29.1	2,180,000			69.4	397,000	18.2
5 : 00			− 47.5	28.0	75.5		
5 : 03			− 109.0	33.0	76.0		
5 : 06			− 169.6	92.5	77.1		
5 : 09			− 231.5	154.0	77.5		
	58.6	487,000			76.5	27,400	5.6
9 : 06 A. M.			− 14.2	50.4	64.6		
9 : 09			− 16.3	48.5	64.8		
9 : 12			− 18.4	46.0	64.4		
9 : 15			− 19.2	44.0	63.2		
	23.1	3,212,000			64.2	750,000	23.3
10 : 42			9.0	86.3	77.3		
10 : 45			14.0	85.0	71.0		
10 : 48			− 5.3	74.6	79.9		
10 : 51			− 4.0	72.0	76.0		
	73.4	284,000			76.0	10,400	3.7
12 : 00			− 3.5	69.2	72.7		
12 : 03			− 30.2	43.3	73.6		
12 : 06			− 51.6	21.6	73.2		
12 : 09			− 74.4	− 2.0	72.4		
	48.9	1,070,000			73.0	116,000	10.8

LIGHT SENSITIVENESS AT DIFFERENT TEMPERATURES. — *Continued.*

Time.	Temperature, Centigrade.	Resistance of Cell in Ohms.	Readings.		Deflection, mm.	Change of Resistance.	Percentage Change of Resistance
2 : 19 P. M.			− 7.0	62.7	69.7		
2 : 22			− 11.2	58.7	69.9		
2 : 25			− 14.7	53.6	68.3		
2 : 28			− 18.2	51.3	69.5		
	32.2	2,410,000			69.4	479,000	19.9

pressure or radium effects. It seems that the decrease of resistance was due to something diffusing from the hydrogen peroxide. Certainly there was no radiation of the slightest penetrating power.

In order to study the nature of this change in the selenium cell, we superimposed a light effect upon the hydrogen peroxide effect.

Hydrogen peroxide of strength 30 per cent. was poured on black paper and black cloth within 4 cm. of the Giltay cell no. 92. Some hydrogen peroxide may have got on to the cell itself. The resistance fell from 2,200,000 ohms to 10,000 ohms. Apparently it did not begin to recover until the hydrogen peroxide had evaporated. The time taken was about 20 minutes. When illuminated at this low resistance by a 1 c.p. light, at 30 cm. distance, there was no appreciable change in the resistance. There was no light effect at 18,000 ohms, but when the cell had recovered to 50,000 ohms, a deflection of 5 mm. was produced on the scale, when the cell was illuminated for 10 seconds. The value of the change in resistance was not measured, but it was very small. These results seem to show in a rough way that where there is already a maximum effect due to hydrogen peroxide, there will be produced no additional effect by superimposing a light effect. Also that the light effect will be correspondingly less as the hydrogen peroxide effect increases.

THE EFFECT OF RADIUM.

Under this head is given : (1) The resistance of the selenium cell at different distances from the radium ; (2) the resistance of the cell when different thicknesses of mica are placed between the cell and the radium ; (3) the recovery of the cell after exposure to radium.

The radium used in these experiments was 3 mgm. of 2 to 3,000,000 activity, kindly lent by Professor Rutherford. It was in a rubber case with a mica cover. The mica cover could be removed.

The selenium cell used was made by Ruhmer and numbered by him 454. Its conductivity was increased about 8 times when exposed to light. The circular area exposed to radium was 2.3 cm. diameter.

The resistance was measured by the ordinary Wheatstone's bridge method. The cell was fixed in a hard rubber case. This case was lowered till it touched the top of a brass cylinder 2 inches in diameter. Cylinders of different lengths were used so that the

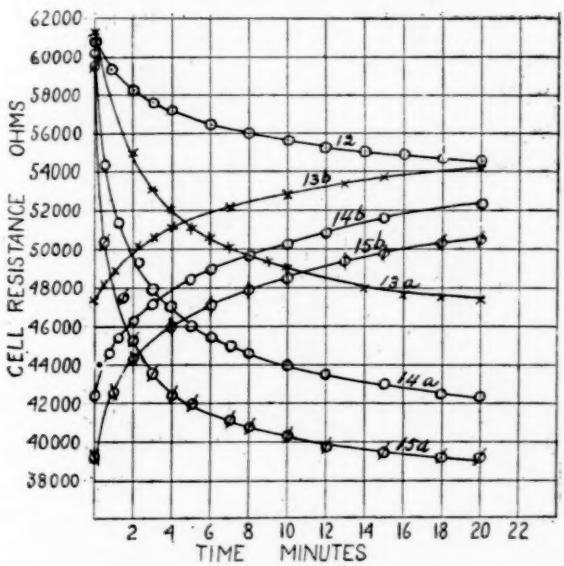

Fig. 11.

effect at different distances could be obtained without disturbing the radium or exposing the cell to light. The results with radium and selenium are shown in the curves of Fig. 11.

Curve 12 shows the decrease of resistance with time when the perpendicular distance from the radium to the cell is 2.6 inches. Curve 13*a* shows the same when the distance is 1.1 inches. Curve 14*a* shows the effect when the distance of the radium is .6 inch, and curve 15*a* is for a perpendicular distance of .1 inch. The

LIGHT SENSITIVENESS AT DIFFERENT TEMPERATURES. — *Continued.*

Time.	Temperature, Centigrade.	Resistance of Cell in Ohms.	Readings.		Deflection, mm.	Change of Resistance.	Percentage Change of Resistance
2 : 19 P. M.			− 7.0	62.7	69.7		
2 : 22			− 11.2	58.7	69.9		
2 : 25			− 14.7	53.6	68.3		
2 : 28			− 18.2	51.3	69.5		
	32.2	2,410,000			69.4	479,000	19.9

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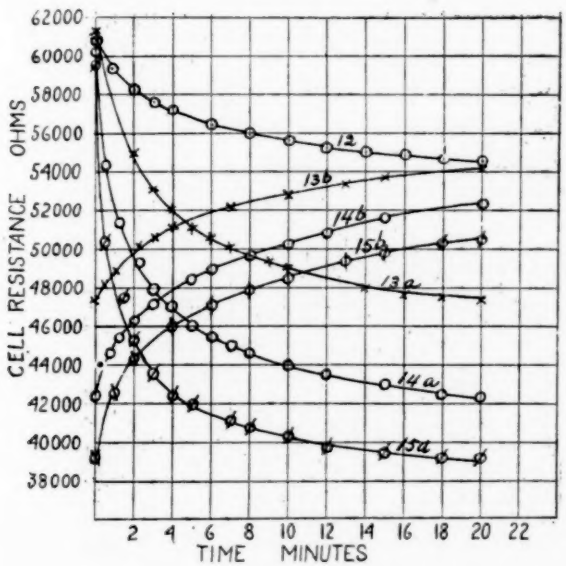

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general results of the above-mentioned curves and other similar ones are shown in curve 16 (Fig. 10) in which the exposure is taken for 10 minutes.

The number of particles or rays striking the surface of the sele-

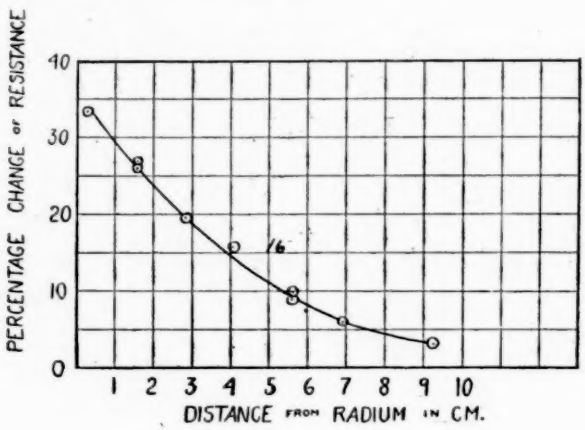

Fig. 12.

nium should vary as the solid angle, if there were no absorption in the intervening space. The following table shows how the change of resistance varies with the solid angle.

Distance of the Radium, mm.	2.6	15.3	27.9	40.6	66	78.7	102.5
Solid angle.	1.5π	0.4π	0.15π	0.078π	0.03π	0.022π	0.012π
Percentage change of resistance.	33.0	26.5	18.5	16.0	9.5	6.2	3.0

From these data it is seen that the change of resistance does not vary as the solid angle. The absorption of the particles by the air does not appear to be capable of explaining the discrepancy. We know that for intense lights the change of resistance is not proportional to the intensity of the light. In the same way we might expect for large values of the solid angle that the change of resistance would not be proportional to the number of particles falling on the selenium surface. Further discussion of the foregoing results will be postponed until the effect of placing thin sheets of mica between the radium and the selenium cell has been considered.

The curves of Fig. 13 show the decrease of resistance of the cell with time when the cell is 1.3 cm. away from the radium. The curves show how the effect varies with time with different thicknesses of mica between the cell and the radium. Of course there was 1.3 cm. of air between the cell and the radium in every case. In obtaining the data for curve 18 the radium was covered with a mica sheet .017 cm. thick. For curve 17 there was an additional mica sheet

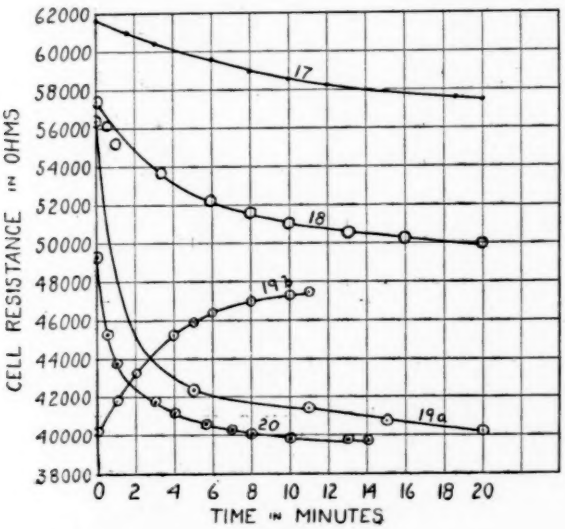

Fig. 13.

.038 cm. thick making a total thickness of .055 cm. But for curves 19*a* and 20 there was no mica over the radium. The difference in these two curves arises from the fact that the state of recovery was not the same in the two cases. Only 14 minutes was allowed for recovery after getting the data for curve 19*a* before taking the observations represented by curve 20.

Fig. 14 shows approximately how the effect varies with different thicknesses of mica interposed. The data for these curves were taken from curves 17, 18 and 19*a*. It could only be approximated however because the state of recovery was different in the several cases. The effect is comparatively very small when .055 cm. of mica is interposed. The absorption of the γ radiation would not warrant such a decrease in the effect. On the other

hand the thinnest piece of mica used would not permit any of the α particles to penetrate it. It therefore follows that some part of the effect is due to the β particles.

The intensity of the β particles after passing through an absorbing medium is expressed by the equation,

$$i = i_0 e^{-\lambda d},$$

where i_0 is the value of the intensity for no absorbtion, d is the thickness of the absorbing material, and λ is the coefficient of absorption.

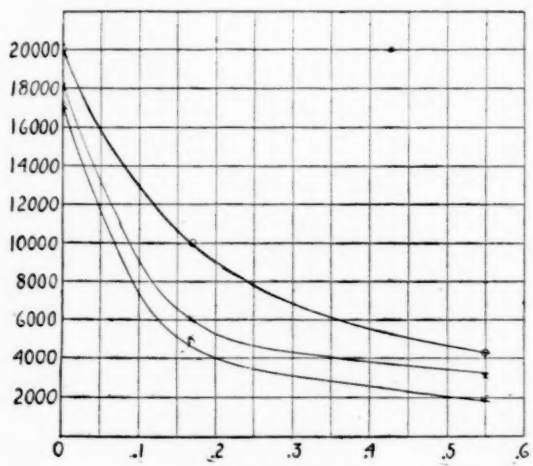

Fig. 14.

To find the coefficient of absorption from our data we may take from curve 23 the intensity of the radiation after passing through .02 and .05 cm. of mica. For either of these thicknesses the intensity of the radiation is about proportional to the change of resistance, and also there can be no α particles in either case. From the previous equation we get for different thicknesses of mica,

$$\lambda = \frac{\log_e \frac{i_1}{i_2}}{-d_1 d_2}.$$

Putting in the values for a 5 minute exposure we get

$$\lambda = 23.0.$$

For a 10-minute exposure as taken from curve 22, the value of the coefficient is

$$\lambda = 14.2.$$

Strutt gives 10.8 for the value of λ, the coefficient of absorption, for the β rays from radium. Our values are of the same order of magnitude as that given by Strutt.

In order to see if the α particles play any part in the change of resistance, we may refer again to curve 23. If we assume the density law for the absorption of the α particles, they would be almost completely absorbed by .015 cm. of mica. Assume then that all the change of resistance, 5,200 ohms, when .015 cm. of mica is interposed is due to the β rays. By use of the equation $\log i/i_0 = \epsilon^{-\lambda d}$ it is found that if 5,200 represents the intensity of the β rays after passing through a thickness of mica of .015 cm., then the intensity for no absorption should be represented by 7,400. For these intensities the change of resistance should vary less rapidly than the change of intensity, so that for zero thickness of mica, we should expect a change in resistance of less than 7,400 ohms. But the curve 23 shows that the change of resistance for no mica interposed is 17,000 ohms. Since this value represents a larger value of the intensity, we are led to believe that where there is no absorption the α particles have a greater effect than do the β particles. However we do not know whether any of this effect which we have attributed to the α particles may be due to the emanation.

Again referring to the variation of resistance with distance from the radium it is seen that beyond 5 cm. the change of resistance is almost proportional to the solid angle subtended. The slight discrepancy here can be accounted for by the absorption of the β particles in air. The γ particles would suffer no appreciable absorption under such circumstances. For distances less than 5 cm. the change of resistance decreases less rapidly than does the solid angle. But no conclusions can be drawn from this since the change of resistance is not proportional to the intensity.

The effect of radium on the selenium cell has been investigated by Himstedt and Bloch. Himstedt[1] found a one per cent. decrease of resistance in the selenium cell. The radium rays had to pass

[1] Ann. der Physik, 1901, 4, p. 535.

through an opaque paper and one centimeter of air. Bloch[1] found a cell to decrease from 30,100 to 29,000 ohms and this through a sheet of paper. In another case a cell decreased from 654,000 to 640,000 ohms in 10 minutes time. The radium used was of activity about 1,000. Himstedt does not state the activity of his radium, but judging from the percentage decrease it was probably not much different from that used by Bloch. In either of these cases the effect was so slight and the data so limited that we could not expect to arrive at any conclusion as to how the radium affected the selenium.

The recovery of the selenium cell after exposure to radium is shown in curves 13*b*, 14*b*, 15*b*, 19*b* and 26. It is apparent that the recovery is not as rapid as the recovery from the same decrease of resistance due to light. However it does return eventually to approximately the initial value. In curve 26 (Fig. 15) is shown the recovery when there was about a 35 per cent. decrease of resistance due to radium. Curve 25 shows the recovery when the same Ruhmer cell had its resistance decreased 87 per cent. by light. Unfortunately the recovery for a 35 per cent. decrease was not studied, but the recovery would evidently be much faster. In curve 25 is shown the recovery of cell 4 when there was a 10 per cent. decrease of resistance by light. The conclusion is that for the same decrease of resistance the recovery from the effect of radium is much slower than the recovery from the effect of light.

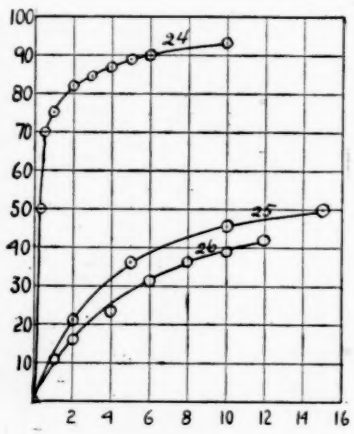

Fig. 15.

DISCUSSION OF RESULTS.

The purpose of this paper is to examine the effects of the various agencies that change the resistance of the selenium cell and to cor-

[1] Compt. Rendus, CXXXII., p. 914.

relate them in so far as possible. The selenium cell varies in resistance when exposed to temperature change, to pressure change, to light, to radium rays, to hydrogen peroxide and to other conditions not mentioned in this paper. The question arises as to whether these resistance changes are ultimately due to the same cause. We may state at the outset that we cannot completely correlate our results but we hope that in the near future an hypothesis may be set up which will satisfactorily and completely explain all the various selenium phenomena.

First as regards pressure. The pressure effect must be a genuine effect in the selenium. The change in resistance due to pressure cannot be due to change in contact resistance between the selenium and the electrodes. For suppose,

R is the contact resistance.

r is the variable resistance in the selenium itself.

ΔR is the change of contact resistance due to pressure.

Δr is the change of resistance due to light.

Then when the pressure is off, the percentage change of resistance in the whole cell would be

$$\frac{\Delta r}{R + r} \times 100.$$

When the pressure is on the cell, the light effect being the same, the percentage change of resistance would be

$$\frac{\Delta r}{R + \Delta R + r} \times 100.$$

The ratio of the percentages of change would be,

$$\frac{\text{pressure on}}{\text{pressure off}} = \frac{R + r}{R + \Delta R + r}.$$

If the pressure decreased the contact resistance, ΔR would be negative, and the ratio necessarily greater than one. On examining our data it is seen that the value of this ratio is slightly less than unity in every case, and it is clear then that the change of resistance due to pressure cannot be due to change of contact resistance. We may also arrive at the same result by other reasoning. $\Delta R/R$ is

considerable, sometimes approaching values as large as .5. If the change due to pressure were in the contact between the selenium and the electrodes, we should expect a variation in the light sensitiveness approaching values as large as 50 per cent. But in comparison with values as large as 50 per cent. the variation may be considered zero.

Next consider the similarity of the nature of the decrease of resistance due to temperature and that due to pressure. It is to be noted that in pressure effects as well as in temperature effects the sensitiveness of the cell to light seems to be a function of the resistance of the given cell. This can best be understood by looking at the curves of Fig. 16. In I., II., III. and IV. is shown how the sensitiveness varies with the resistance, when the change of

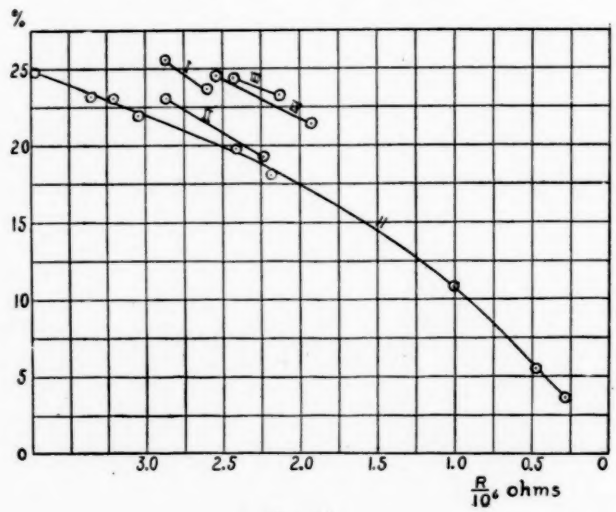

Fig. 16.

resistance is produced by a variation of the pressure. In series IV. of the observations on the sensitiveness at different pressures it was estimated that .4 sq. cm. area of the cell was exposed to light. Consequently to find the sensitiveness for the exposure of one square centimeter area the value found previously was divided by .4. For the same reason the other three series were divided by .3. In curve II is shown how the sensitiveness varies with the resistance, when the change of resistance is produced by temperature variation.

Within the limits of error of the experiments it is seen that the rate of change of sensitiveness is the same for all the curves, and we may conclude that the sensitiveness to light is probably dependent upon the resistance, whether that be conditioned by temperature or pressure.

It is seen from the previous data that the pressure effects take place almost instantly upon the application of the pressure. With the exception of a small lag the selenium cell, when exposed to temperature changes in a liquid bath, rises to a position of electrical equilibrium even quicker than does an ordinary thermometer. This correlation is what we should expect. However if the quantity of selenium in the cell is great and the cell is surrounded by an air bath, the cell may be quite sluggish in changing its resistance with the temperature of the bath.

The rough work done with hydrogen peroxide will not of itself permit of any definite conclusions, but the following seems to be true. The change of resistance in the dark is of such a nature that if light is allowed to fall on the cell there is no additional change in the resistance, providing only that the change produced by the hydrogen peroxide is sufficiently great. The rate of recovery from exposure to hydrogen peroxide is very slow, resembling the recovery from the effects of radium.

With increased temperature or increased pressure, or hydrogen peroxide exposure the change of resistance due to light is correspondingly less. So far as electrical conductivity is concerned, all these conditions seem to take the selenium toward a certain equilibrium state.

Summary.

1. The selenium cell changes its resistance with a change in the mechanical pressure on its surface. The pressure produces a real change in the resistance of the selenium itself. For the cases noted the percentage change of resistance for one atmosphere lies between .05 and .30. This value is also a function of the temperature and the electromotive force applied in measuring the resistance.

2. An increase of pressure or a rise of temperature lowers the light sensitiveness of the selenium cell.

3. The light sensitiveness is a function of the resistance of the given cell, whether this resistance be conditioned mainly by temperature, light, radium or hydrogen peroxide.

4. The effect of radium and of hydrogen peroxide is to decrease the resistance very markedly, as much as 35 and 99 per cent. respectively.

This work was carried on in the Physics laboratory of the University of Illinois and the writers wish to acknowledge their indebtedness, to Professor A. P. Carman for apparatus placed at their disposal and for his help in the early part of the work; also to Professor E. Rutherford for kindly lending the radium used, and to Professor O. W. Richardson for several valuable suggestions.

UNIVERSITY OF ILLINOIS,
PRINCETON UNIVERSITY,
November 1, 1907.

PENDULUM COINCIDENCES DETERMINED BY SHADOW REËNFORCEMENTS, SHADOW MICROMETRY, ETC.

By C. Barus.

1. Let two similar pendulums be mounted, one normally behind the other relatively to their nearly parallel planes of vibration. Provide each (light cork attachment and incision) with a small square of wire gauze (one inch square) of about a millimeter mesh, the planes of the gauze being nearly normally behind each other, about six inches apart, and parallel to the plane of vibration. Let the threads of the gauze be respectively horizontal and vertical (or in general nearly parallel in the two cases) and let the pendulums be swung over about the same arc.

2. When the pendulums are at rest, the observer looking from a distance through one gauze at the other with a bright background behind it (white paper, spot of sunlight, ground glass and lamp), sees the usual shadow reënforcements, in form of more or less equidistant horizontal and vertical dark bands. When the pendulums move the vertical bands are usually wiped out except at the elongations, because the corresponding wires of the gauze sweep past each other too rapidly to be recorded by the eye. The horizontal bands, however, remain in the field, for there is no translation in the direction of the axis of a pendulum; but there is rotation. Hence, as the pendulums sweep over any angle α with respect to each other, the originally horizontal shadow bands sweep over a large multiple of α. Thus the shadow bands are seen to topple from an angle of more than 45 degrees above the horizontal, to more than 45 degrees below it, except at the moment of coincidence, when they are for an instant stationary and nearly horizontal. At this instant the hands of a stop watch may be released and arrested again at the next coincidence.

If α be the angle between the nearly horizontal wires of the gauze

and γ the angle of the shadow bands with the direction of either of the wires; if a is the distance apart of the wires and b the projection of the a of one on the plane of the other by the eye of the observer, so that a and b are the virtual distances apart of the effective wires, we may write $\tan \gamma = a \tan \alpha/(a - b \sec \alpha)$, and thus γ is liable to be greater than 90 degrees. If α is small $\tan \gamma = a\alpha/[(a - b) - a\alpha^2/2]$ and for very small α, $\tan \gamma = a\alpha/(a - b)$. Since a and b are nearly equal the rapid increase of $\tan \gamma$ as α passes through zero is manifest.

3. The phenomenon is very beautiful. With a larger square of wire gauze (6 inches square and $\frac{1}{8}$-inch mesh) it may be easily shown to a class on a light background. When the two pendulums are all but stationary, the horizontal bands are also nearly so, while the vertical bands are now permanently in the field magnifying the motion and becoming fixed at the coincidences. Pendulums may be thus compared which are scarcely seen to move, though for this purpose the method of the next paragraph is still better. Finally the phenomenon may be projected in various ways, but in no case are the results so satisfactory as the above. If two pendulums vibrate at right angles to each other, the elongations of the vertical pendulum are useful in the same way, horizontal bands recurring and marking the coincidences of the upper elongation of the vertical pendulum and the mean position of the horizontal pendulum.

4. The most fascinating reinforcements are obtainable from the superposition of two identical sets of concentric circles, which may be drawn or photographed on glass plates. If the circles are equidistant the hyperbolæ of Young's interferences are strikingly brought out for all distances apart of the centers. If these shadow bands are to be straight lines, equidistant and at right angles to the lines joining the centers of the two plates, the nth and $(n + 1)$th radii of the circles of each of the identical plates in the mth black band must be compatible with $r_{m+n+1}^2 - r_{n+1}^2 = r_{m+n}^2 - r_n^2$ where r_n and r_{m+n}, r_{n+1} and r_{m+n+1} are the radii from the centers, respectively, to the two consecutive intersections on the same dark band. Hence the radii may be put $r_n = \sqrt{n}$; or the linear bands are obtained by superposing two zone plates. A disk of about one half centimeter in diameter or larger is satisfactory.

To use this arrangement as a micrometer, suppose the distances to be measured by the relative motion of the two superposed plates are in a horizontal direction, and let x be one of these small distances. Let the plates be placed in a vertical plane through x, and so that the center, c, of one set of circles may be a centimeters above the center, c', of the other set of circles. Then if γ is the angle of the dark bands (normal to cc') with the horizontal x, $\tan \gamma = x/a$. Thus if a is one tenth millimeter, a displacement of x will rotate the originally horizontal bands (cc' vertical), rising or falling according to the relative motion, roughly about as follows:

$x =$	.002	.005	.01	.03	.1	millimeter
$\pm\gamma =$	1°	3°	6°	17°	45°	

The distance apart of the bands is uniformly $1/2\sqrt{x^2 + a^2}$ or $1/2(x^2 + a^2)$ of the distance apart of centers; and they thus become wider as x and a decrease, vanishing at infinity in case of coincidence. Finally if a medium could be constructed in which the index of refraction increases about as the normal distance from the lines joining the centers, the present phenomenon would approximately replace Young's interferences.

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A SATISFACTORY FORM OF HIGH RESISTANCE.

BY G. W. STEWART.

A DISCUSSION[1] of the measurement of current by means of the steady deflection of an electrometer needle called my attention to the fact that there is an increasing demand for a satisfactory form of a very high resistance. Rutherford, in the above reference, states that Bronson was unable to obtain sufficiently high and yet constant resistances; that tubes of xylol had too great a resistance while special carbon resistances were not sufficiently constant.

The low conductivity of carbon has naturally attracted the attention of those looking for satisfactory forms of high resistances, but the lack of constancy has always been a very great disadvantage. Longden[2] has published several methods of making carbon resistances which prove to be quite satisfactory, but, as he states, all the resistances increase with the time. Smoke films deposited on glass, hardened by exposure to alcohol vapor, and then covered with shellac varnish, india-rubber varnish or paraffin wax, proved to be the most satisfactory.

This note makes record of a very convenient and satisfactory form of high resistance in which carbon is utilized, and also furnishes data as to its constancy. The use of a transparent lacquer called "Zapon" in the shop of the laboratory, directed my attention to its possible combination with carbon in the formation of a permanent high resistance. The lacquer consists of soluble cotton dissolved in certain mixed solvents, the chief ingredient of which is amyl acetate. When dry, there is left a film of pyroxyline which is elastic, is not subject to ordinary changes in temperature, does not evaporate, does not crack, and is a good insulator.[3] These

[1] Rutherford's Radioactivity, 1906, p. 104.

[2] Longden, PHYSICAL REVIEW, 15, 1902, p. 355.

[3] The General Electric Company controls a patent (No. 687,517) for the use of pyroxyline dissolved in a solution containing amyl acetate as applied to electrical conductors as an insulating material. This method of insulating wire is now in commercial use (Elec. World, Vol. XLIX., No. 14, April 6, 1907, p. 686).

characteristics are extremely important, and the possession of them by this lacquer is the occasion of this article. It occurred to me that if lampblack were mixed with this lacquer and spread with a brush upon an insulator, a permanent and yet high resistance might be obtained. Experiment has proven this to be the case. The commercial "Germantown" lampblack and the lacquer known as "Zapon L"[1] were used in the experiments. The results obtained can be best described by discussing the several points of excellence of such resistances.

Convenience. — As already suggested, the resistance is obtained by spreading the mixture of lampblack and zapon upon an insulating surface. The conductivity of the films thus produced can be easily regulated by the amount of lampblack used and the thickness to which the lacquer is spread with the brush. By trial, I secured a variation in resistance from 3,000 ohms to 3,000,000 ohms with a film approximately 3 mm. long and 2 mm. wide. In order to control the range in constructing high resistances, mixtures with varying proportions of lampblack can be kept on hand. In some experiments, resistances as high as 40,000 megohms are desired. With a film similar to the one just mentioned, it would be possible to secure this enormous resistance by a strip 0.2 mm. wide and 4 meters long. Doubtless films of less conductivity can be secured readily, thus making the length required more easily obtainable.

A further convenience is that the process of making the films is simple and easy of execution, requiring no special apparatus whatever. The forms in which the resistances can be made are unlimited, and can be determined by the purpose for which the resistance is intended. Thus far, I have experimented only with hard rubber as a base for the lacquer, and the different forms in which the rubber is readily obtainable means great convenience in the construction of such resistances. It should be stated that the sample of zapon I have used will not cling very satisfactorily to a very smooth surface, unroughened glass for example.

Permanency. — Films of shellac, india-rubber varnish, paraffin, and no doubt other substances have been proposed as binders for the

[1] "Zapon L" is the trade name given by the manufacturers, the Celluloid Zapon Company, Stamford, Conn.

carbon particles, the object being to make the resistance as permanent as possible. A film of pyroxyline has a decided advantage from the standpoint of permanency, for it will neither crack readily nor deteriorate.

In securing permanency care must be taken to eliminate changes in the contact between the terminals and the film. This is done by making the terminals a part of the base itself. In some of the experiments, this condition was secured by making the terminals of copper plugs screwed into the rubber plate. Longden [1] solved this difficulty by making the terminals of deposited silver films.

Experiments were made to test the variation of such resistances with time. Two resistances made in January were found to have varied but 3 per cent. five months later. Films of less conductivity do not age so quickly. For example, one of very much less conductivity had a value of 4.13 megohms on May 11, the day following the manufacture; on May 13 a value of 3.61 megohms; on May 15, a value of 3.45 megohms, on May 20, a value of 3.35 megohms. These figures show a variation which is at first quite large, but which grows smaller quite rapidly.

Doubtless a process of aging by baking would bring such films to a practically steady value at once. Of course a resistance which is composed of carbon particles held in position by a hardened film could in no case be as constant as a metallic resistance. It would therefore be necessary to calibrate constructed resistances from time to time, but with such occasional calibration they would remain sufficiently constant for fairly accurate work.

A variation of the resistance with the impressed voltage would not be surprising. In my first experiments, I found that the resistance decreased with increase of voltage. However, after making the terminals more a part of the base itself, as already suggested, I found the variation to be less than one half of one per cent. with a variation of voltage of 1,000 per cent. In fact, I did not detect any regular variation with voltage at all, for the sensitiveness of the apparatus would permit the detection of a variation no less than that already stated. The observations were made by connecting the resistances in series with a source of voltage and a galvanometer.

[1] Longden, loc. cit.

The resistance consisted of a film about 3 mm. long and 2 mm. wide. Readings were taken with films ranging from 100,000 ohms to 3 megohms. In each case the voltage was varied at least 1,000 per cent., the actual values used depending upon the sensitiveness of the galvanometer.

The question as to the variation with voltage is an important one, in as much as in the electrometer method of measuring ionization currents, the voltage employed varies with the current to be measured. The experiments I have performed do not prove that these carbon resistances remain constant at small voltages (0.01 of a volt is sometimes used with a resistance of 30,000 megohms.) From general considerations, however, it would seem highly probable that there would be less, instead of greater, variation at lower voltages. Doubtless this form of resistance would therefore be satisfactory in the measurements of ionization currents. Apparatus with which to prove this point was not at my disposal.

As would be expected there is a variation in these carbon resistances with the temperature. A number of observations were made through small ranges of temperature, and the results show a variation of from 0.1 to 0.15 per cent. per degree centigrade. Of course this figure will depend somewhat upon the base employed for the film, and consequently must be determined for each arrangement.

The permanence of the film of pyroxyline, the fact that it can be subjected to ordinary ranges of temperature without cracking or deteriorating, would indicate that properly constructed resistances would give satisfaction for an indefinite time. Furthermore, resistances of a few megohms might easily be enclosed in sealed tubes in order to obviate any variations due to moisture.[1] It is believed, therefore, that this note suggests a form of high resistance which is both convenient and reasonably permanent, subjected only to very slow changes in resistance with time, and which will prove especially satisfactory where very high resistances of thousands of megohms are desired.

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[1] Since writing the above, I have found that these resistances increase somewhat with increase in humidity. Whether this is due to the occlusion of water vapor by the carbon or to the swelling of the pyroxyline film, has not been ascertained.

ON PHYSICAL LINES OF FORCE IN ELECTRICAL THEORY.

BY FERNANDO SANFORD.

IN most of the discussions of electrical theory since the publication of Maxwell's great treatise the physical lines of force assumed by Faraday have played an important part. There have been various concepts as to the character of these lines of force, but apparently all who have used them have agreed in assigning to them the property of contraction lengthwise combined with another property equivalent to a repulsion at right angles to their length. Faraday apparently thought of them as elastic cords attached at their ends to unlike charges of electricity and tending to shorten and become thicker like muscle fibers. Maxwell apparently conceived of them as lines of polarized molecules imbedded in a dielectric medium, something after the order of the hypothetical Grotthus chain in electrolysis. Other writers have assumed the ether to consist of cells or molecules of positive and negative electricity and to be sheared by electric stresses so that positive electricity appears at one boundary of the stress and negative electricity at the other, while J. J. Thomson has conceived of them as some sort of vortex filaments running through, but differentiated from, the rest of the ether and terminating in a positive atom at one end and a negative atom or electron (corpuscle) at the other.

It has seemed to the present writer that the most logical and complete development of the idea of physical lines or tubes of force is to be found in the writings of Professor J. J. Thomson, and it is the purpose of the present paper to discuss some of Thomson's ideas and to inquire into the validity of some of the hypotheses which he has built upon them.

Thomson has realized clearly that physical lines or tubes of force must be finite in number. He says (Experimental Researches, 3): "In the mathematical theory of electricity there is nothing to indi-

cate that there is any limit to the extent to which a field of electric force can be subdivided up into tubes of continually diminishing strength; the case is however different if we regard these tubes of force as being no longer merely a form of mathematical expression, but as real physical quantities having definite sizes and shapes. If we take this view, we naturally regard the tubes as being all of the same strength, and we shall see reasons for believing that this strength is such that when they terminate on a conductor there is at the end of the tube a charge of negative electricity equal to that which in the theory of electrolysis we associate with an atom of a monovalent element such as chlorine.

"This strength of the unit tubes is adopted because the phenomena of electrolysis show that it is a natural unit, and that fractional parts of this unit do not exist, at any rate in electricity that has passed through an electrolyte."

That Thomson still holds to this definition of a unit Faraday tube may be seen from his discussion of the constitution of the atom in his recent work on "Electricity and Matter." He says (Elec. and Mat., p. 133): "Now, on the electrical view of chemical combination, a univalent atom has one unit charge, if we take as our unit of charge the charge on the corpuscle; the atom is therefore the beginning or end of one unit Faraday tube: the beginning if the charge on the atom is positive, the end if the charge is negative. A divalent atom has two units of charge and therefore it is the origin or termination of two unit Faraday tubes. Thus, if we interpret the 'bond' of the chemist as indicating a unit Faraday tube, connecting charged atoms in the molecule, the structural formulæ of the chemist can be at once translated into the electrical theory."

This concept of the tube of force would seem to make the total number of Faraday tubes in the physical universe a constant, *i. e.*, one for each pair of unit positive and negative charges, and Thomson has recognized this necessity. He says (Ex. Res., 4): "These tubes also resemble the molecules of a gas in another respect, as we regard them as incapable of destruction or creation."

This would seem to mean that each unit charge of negative electricity, *i. e.*, each electron (corpuscle) in the physical universe is indissolubly connected by a unit tube of force to its own particular

positive atom, and that these unit positive and negative charges cannot change partners because to do so would oblige them to part with their own tube of force, or atomic bond, and take on a new one, and this would involve at least the temporary destruction of both tubes of force.

This plain deduction from all the possible definitions of unit physical tubes of force seems to have been overlooked by physicists who have adopted the theory, and it is inconsistent with our understanding of many of the commonest chemical phenomena. All chemical reactions are apparently dependent upon the ability of the electropositive and electronegative constituents of the reacting molecules to exchange partners.

Again, since an electron or a monovalent atom can have only one tube of force ending or beginning upon it, it can be acted upon by no other electric force whatever. An electron in any electric field is acted upon by only its own tube of force and is impelled only toward its own positive atom, and no electric force whatever can cause it to deviate from the direction of its own tube of force.

This would make it impossible for tubes of force to stretch across from one charged conductor to another, since there would be nothing at either end to hold the unit charges to their respective conductors, hence no tube of force could ever be of more than molecular dimensions.

It also follows from this assumption of unit tubes and the accepted electrical theory which goes with it that an electron can have no magnetic field of its own, since in the theory the magnetic field is due to the motion of tubes of force in a direction at right angles to their length, and an electron can have no tubes of force projecting at right angles to its direction of motion. This would seem to make necessary some other interpretation of Thomson's calculation of the electric mass of the electrons thrown off by radium in Kauffmann's experiments (Phil. Mag., 8, 331 ; Elec. and Mat., Chap. II.). Here Thomson has assumed a great number of Faraday tubes radiating from an electron as from a charged sphere, and by their motion at right angles to their length setting up an electromagnetic field. If it can be shown, as seems to be the case, that a single electron moving through the ether may have an electromagnetic

field, and hence an "electrical mass," it would seem that the idea of the unit tube of force must be abandoned or that the magnetic field must be explained by something other than the transverse motion of these tubes.

But this is not the only place where the Faraday tubes seem inadequate to explain the phenomena for which they were invented. In the attempt to explain the electromagnetic field of a current by the transverse motion of Faraday tubes it seems necessary to assume that positive electricity is leaving one plate of the battery and negative electricity the other (Ex. Res., 40; Elec. and Mat., 17) and that these opposite charges meet in the conductor where the Faraday tubes shrink to molecular dimensions. This means that one half of any electric current consists of positive charges traveling in one direction while the other half consists of negative charges traveling in the opposite direction to meet them. In other words, in any closed electric circuit one half of the conductor contains positive atoms in motion and the other half contains negative electrons moving to meet them. This seems contrary to experience, since there is no evidence that the positive atoms of a solid conductor move with the current.

On the other hand, there is strong evidence that such motion does not take place. For consider a battery composed of a zinc and an iron plate joined by a copper wire. According to the theory, a tube of force must start from a positive iron atom and a negative zinc electron and must run along between the two halves of the conducting wire carrying the iron atom at one end and the electron at the other until these meet to form a neutral iron atom in the copper wire. As we have already seen, the Faraday tube cannot release one positive atom and seize another, since in so doing it would have to exist for a finite time with a unit charge at only one end, which is contrary to the definition of all physical lines or tubes of force as well as contradictory to the third law of motion.

A similar difficulty is met with in explaining the induction of one current by another. Here the Faraday tube starting from the positive and negative ends of the primary circuit must break when it reaches the secondary circuit (Ex. Res., 41), and by taking up two unit charges from a molecule in this circuit must divide into two

Faraday tubes, destroying as it does so the Faraday tube which originally held together the positive and negative parts of the atom which it separates. When it leaves these positive and negative parts of the atom at the other side of the secondary circuit, it must again break away from both and its free ends must unite, while a new Faraday tube comes into existence between the charged parts of the atom which now meet again in the secondary circuit.

Still another difficulty is met with in the use of the concept of Faraday tubes in the Electromagnetic Theory of Light. Here the source of light is supposed to emit Faraday tubes which move through the ether transversely to their length (Ex. Res., 42). From this point of view, a beam of plane polarized light consists of a great number of straight parallel Faraday tubes traveling through the ether at right angles to their length and with the velocity of light.

Since a beam of light has definite boundaries, these Faraday tubes must be of finite length certainly not greater than the transverse diameter of the beam, and each must carry a unit positive charge at one end and a unit negative charge at the other, *i. e.*, each Faraday tube must have a positive atom at one end and an electron at the other. This, of course, is entirely contrary to experience. Furthermore, Thomson's calculation of the electrical mass of a positive atom or electron having unit charge leads to the conclusion that this electrical mass would be infinite for charges moving with the velocity of light. Hence, from Thomson's assumptions a beam of plane polarized light consists of a very great number of Faraday tubes, each with an infinite mass at each end, moving with the velocity of light.

The above examples are cited to show the inadequacy of physical lines or tubes of force for explaining the ordinary phenomena of electricity. On the other hand, a mere mathematical line of force does not explain anything. It would seem that as long as electrical phenomena are explained by attractions between positive and negative charges either the notion of action at a distance must be revived or some kind of a physical line of force must be assumed as attached at its ends to these charges and by its contraction pulling them together.

If, on the other hand, electric phenomena may be explained by repulsions due to a pressure exerted by the electrons upon the surrounding ether, no physical lines of force are necessary, and no properties but those required by the elastic solid theory of light need be attributed to the ether.

STANFORD UNIVERSITY,
December, 1907.

STUDIES IN THERMO-LUMINESCENCE.

VARIATIONS IN THE DECAY OF PHOSPHORESCENCE IN SIDOT BLENDE PRODUCED BY HEATING.

BY C. A. PIERCE.

THE following paper deals with a quantitative study of the phosphorescence and thermo-luminescence of Sidot blende at temperatures ranging from room temperature to 300° C. The decay of the total intensity of phosphorescence of Sidot blende at ordinary temperatures, as well as the decay of individual bands has been studied by Nichols and Merritt.[1] No attempt has been made in the following paper to study the behavior of individual bands because of the difficulty of measuring very low intensities of light.

The apparatus used is similar in many respects to that employed by Nichols and Merritt to measure the total intensity, some necessary changes being made to adapt it to present conditions. The Sidot blende,[2] in powder form, was contained in a shallow tin dish which was supported on a firm base. The phosphorescence was excited by light from a Lummer mercury lamp. The powder was heated by a small electric furnace, which was mounted so as to move on a track, in order that the powder might remain undisturbed. The temperature of the powder was measured by a thermo-couple, one junction of which was imbedded in the powder, the other junction being kept at constant temperature by melting ice contained in a Dewar bulb. Another set of thermo-junctions was used to adjust the temperature of the furnace before heating the powder. There were four of these junctions, so placed that one junction came at each of the four corners of the powder dish when it was in the furnace. The intensity of the phosphorescent light was compared with a standard light by means of a Lum-

[1] PHYSICAL REVIEW, Vol. XXII., No. 5, May, 1906; XXIII., No. 1, July, 1906.

[2] The powder used in these experiments was "Emanationspulver," which, while a zinc sulphide preparation, is not the Sidot blende used in most of the experiments of Nichols and Merritt.

mer-Brodhun photometer. On account of the low intensity of the phosphorescent light, it was admitted directly to the double glass prism in the photometer. Light from the center of an acetylene flame formed the standard. Colored glass was placed in front of the flame to obtain a color match, and equality of illumination in the photometer was obtained by moving the standard light.

It was found impossible to project the exciting light on to the powder without the use of a mirror. The phosphorescent light was reflected into the photometer by another mirror. A window, composed of a thin piece of mica and a piece of plate glass separated by an air space, allowed the phosphorescence to be measured when the powder was in the furnace. The mirrors were so arranged that the powder could be excited either when in the furnace or outside.

Since the observer worked alone, and in a dark room, it was necessary that the measurements be recorded automatically. The opening and closing of the shutter on the exciting lamp was recorded on a chronograph as was the beginning and end of heating. The times at which the photometer measurements were made as well as the positions of the standard lamp were recorded by pushing a button. The different keys and levers were placed so that the observer could sit with his eye at the telescope of the photometer and make all the manipulations necessary for a complete run.

Before a set of observations, the observer remained in the dark room long enough for his eyes to become sensitive to small intensities of light. At the beginning of each run, the Sidot blende was exposed to infra-red rays for one minute and then allowed to remain in darkness for five minutes before exposure to the exciting light. Nichols and Merritt have found that exposure to infra-red rays will suppress the phosphorescence almost immediately. In the present experiments it was found to be difficult, if not impossible, to obtain a source of infra-red powerful enough to destroy the thermal effect to such an extent that a temperature of about 350 degrees would not cause thermo-luminescence. But an exposure of one minute to a sixteen candle power electric lamp through thin rubber was found to be of sufficient effect to reduce the thermo-phosphorescence, even after the strongest excitation, to such an extent that it could

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not be measured in the photometer. The lamp was held two inches from the powder during the infra-red exposure and heated it somewhat. The wait of five minutes was sufficient, however, to allow the powder to cool off practically to room temperature.

The effect of the temperature upon the decay curve, when the Sidot blende is excited and allowed to decay at the same temperature, is shown in Fig. 1. The curves are plotted with

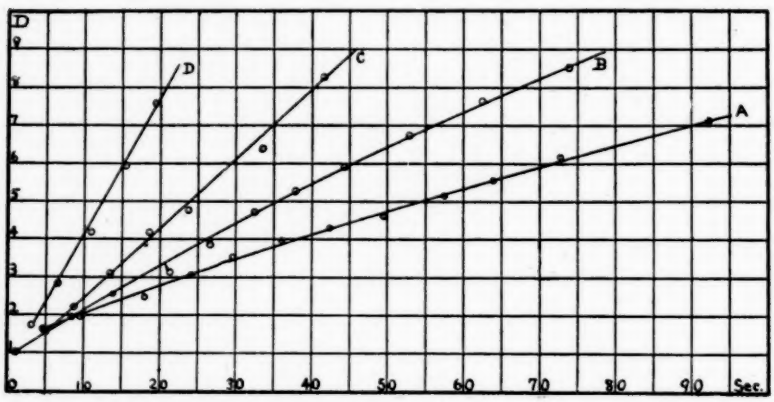


Fig. 1. Effect of temperature during excitation and decay. Excited 40 seconds. Curve *A*, temperature 21° C.; curve *B*, temperature 37° C.; curve *C*, temperature 60° C.; curve *D*, temperature 85° C.

distances of the standard lamp from the photometer screen as ordinates and time reckoned from the end of excitation as abscissæ. The ordinates *D* are inversely proportional to the square root of the intensity. Curves *A* and *B* are concave downward throughout, while *C* and *D* are approximately straight lines. In fact, the points on curve *D* indicate an upward bending.

To determine whether the decay curve becomes straight as the temperature is raised, a series of runs was made with constant length of excitation and constant temperature. The last four runs of the series are shown in Fig. 2. If the curves had been plotted with the actual times as abscissæ, they would coincide. In order that the eye may be able to distinguish readily the points on each curve, the four curves are separated by plotting curve *D* with the abscissæ marked on the figure and displacing the remaining curves each five seconds farther to the right. It is evident that the curves are

straight lines throughout the time of observation, but there is a possibility that the curves would show a downward bending nearer the origin; in fact, such is believed to be the case. The conclusion, that at room temperature the observed part of the decay curve is concave downward and becomes less concave as the temperature is raised, is substantiated by several series of curves which are not reproduced on account of lack of space.

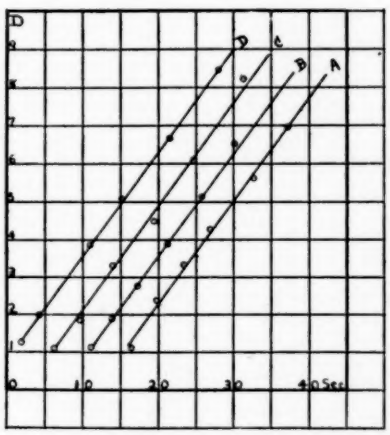


Fig. 2. Effect of temperature during excitation and decay. Excited 400 seconds. Temperature 93° C.

A possible explanation of the changes in the decay curve, which occur when Sidot blende is excited at different temperatures, is deduced as follows. Let it be assumed that the law of decay for a single band in the spectrum is [1]

$$I = \frac{1}{(a + bt)^2}.$$

The decay curve of a band plotted according to this law with D (equal to $I^{-\frac{1}{2}}$) and t as coördinates is a straight line. Let it be assumed that the phosphorescent spectrum of Sidot blende consists of two bands, and let curves AB and CD, Fig. 3, represent the decay of these bands. The decay of the total intensity can be computed by the equation [2]

$$D = I^{-\frac{1}{2}} = \left[\Sigma \frac{1}{(a + bt)} \right]^{-\frac{1}{2}},$$

and is shown in Fig. 3 by the curve OP. This curve is concave downward throughout but approaches a straight line with increase in time. From Figs. 1 and 2 it can be seen that the effect of a higher temperature is to hurry the decay. Hence the slope of the lines representing the decay of the separate bands will be greater at a

[1] The law proposed by H. Becquerel and tested by Nichols and Merritt. See previous reference.

[2] The law proposed by H. Becquerel for the decay of the total intensity when the phosphorescent spectrum consists of more than one band.

higher temperature. *MN*, Fig. 3, represents the decay of the total intensity at the higher temperature. *MN* is concave downward throughout, but if the portion occurring within the first few seconds were not drawn, the remainder of the curve would appear to be a straight line, while under the same conditions, the curve *OP* would still be seen to be concave downward.

The theoretical curves in Fig. 3 represent closely the facts deduced from Figs. 1 and 2. They also fit in with the deductions made by Nichols and Merritt[1] from their work on the decay of the total intensity of Sidot blende, namely, that the decay curve consists of two straight lines which gradually merge into one another. By changing the slopes and intercepts of the lines in Fig. 3 representing the decay of the single bands, a decay curve of the total intensity can be derived which will exactly fit the deductions mentioned above.

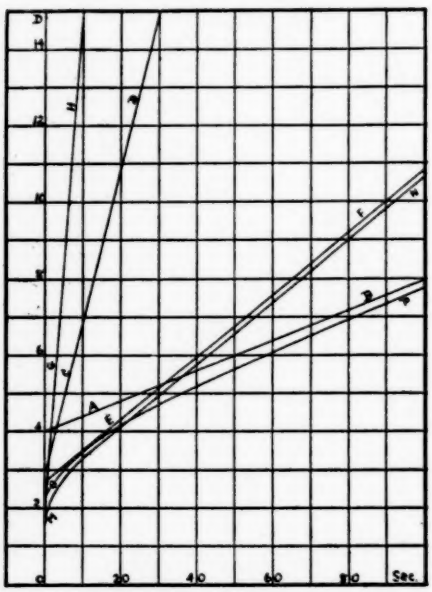


Fig. 3. *AB*, decay of one band at a certain temperature; *CD*, decay of the other band at the same temperature; *OP*, decay of the total intensity due to the two bands; *EF*, decay of the first band at a higher temperature; *GH*, decay of the other band at the higher temperature; *MN*, decay of the total intensity at the higher temperature.

It is impossible to test actual curves of the decay by subtracting a straight line because there is no criterion by which the slope and intercept of the straight line can be estimated. By reference to Fig. 3, it will be seen that the curve of total intensity does not approach closely to the straight line *AB* until *t* becomes quite large.

Other effects of the temperature at which the Sidot blende is excited can be deduced from Fig. 1. The initial intensity evi-

[1] See previous reference.

dently increases with the temperature. The time of decay decreases as the temperature is raised. These deductions will be discussed later in connection with some other curves.

The existence of two bands in the phosphorescence spectrum of Sidot blende is suggested by the two bands in the fluorescence spectrum. Fig. 4 shows the fluorescence spectrum of the sample of Sidot blende used during these experiments when excited by a mercury lamp. The measurements were made on a Lummer-Brodhun spectrophotometer, an acetylene flame forming the standard light. Considerable stray light was visible in the photometer despite all precautions taken to exclude it. This stray light entered through the collimator slit but was separate and distinct from the light reflected from the powder, being, apparently, uniformly distributed throughout the greater part of the spectrum. The curve AB in the figure gives an idea of the error introduced by the stray light, though no great accuracy is claimed for the exact magnitude of the error. One point in the fluorescence curve at 0.485 μ is discarded because it was taken too close to the region of a faint band in the exciting light. Despite the error due to stray light and the necessary inaccuracy of measurements made on violet light, there can be no doubt of the existence of two bands in the fluorescence spectrum, one at 0.53 μ and the other at 0.41 μ.

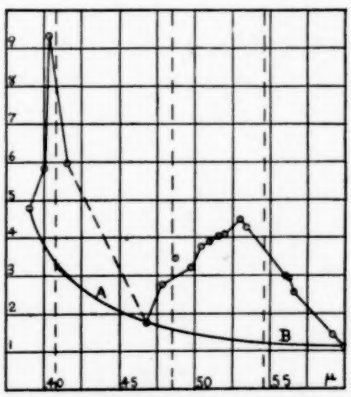


Fig. 4. Fluorescence spectrum of Sidot blende excited by a mercury lamp. Vertical broken lines show positions of the lines in the spectrum of the exciting light. Curve AB shows the error introduced by stray light.

The effect of heating the Sidot blende after it has been excited and allowed to decay at room temperature is illustrated in Fig. 5. The curves are plotted with intensity, equal to D^{-2}, as ordinates and time measured from the moment of heating as abscissae. The effect of increased temperature is to increase the maximum intensity and to cause the maximum intensity to occur sooner after heating. Three sets of these curves are reproduced to give an idea of the ac-

curacy of the observations and to show the manner in which the curves have been produced to zero intensity. Figs. 6 and 7 show curves similar to those in Fig. 5 at different lengths of excitation.

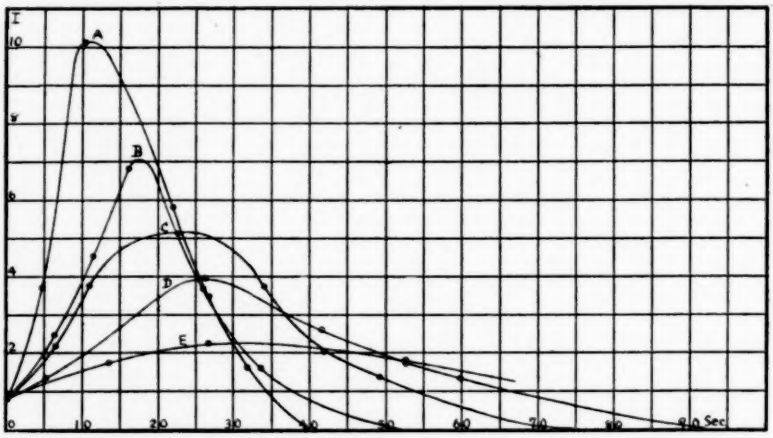


Fig. 5. Effect of heating when the phosphorescence has decayed to an intensity equal to 0.8. Excited 10 seconds at room temperature. Curve *A*, heated to 307° C.; curve *B*, heated to 270° C.; curve *C*, heated to 208° C.; curve *D*, heated to 155° C.; curve *E*, heated to 99° C.

In the case of Fig. 5, the initial intensity immediately after excitation was somewhat greater than $I = 12$. The intensity was allowed

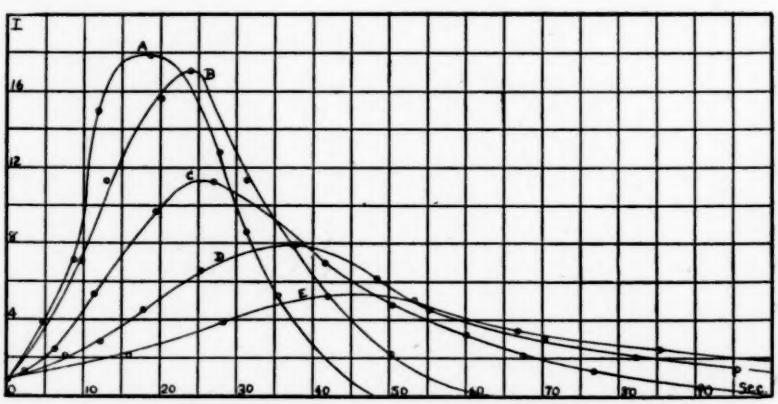


Fig. 6. Curves similar to those in Fig. 5. Excited 80 seconds at room temperature. Curve *A*, heated to 308° C.; curve *B*, heated to 267° C.; curve *C*, heated to 206° C.; curve *D*, heated to 155.5° C.; curve *E*, heated to 99° C.

to decay to $I = 0.8$ when heating was begun. In the case of Fig. 7, the initial intensity was somewhat greater than $I = 37$.

The effect of heating after excitation may be considered in one of two ways.. Either it suddenly releases the energy represented by the phosphorescence, or else it sets up some new reactions in the powder. Though the decay had reached a low intensity before heating was begun in the runs shown in Figs. 5, 6 and 7, yet at this low intensity the decay was slow; hence there may have been considerable energy still left which heating released to give the flash peculiar to thermo-luminescence. If this is the case, the areas

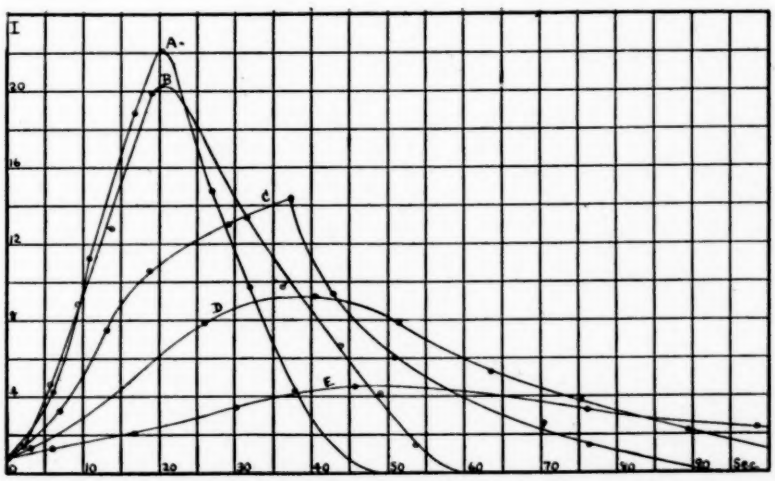
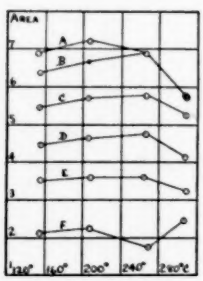


Fig. 7. Curves similar to those in Figs. 5 and 6. Excited 320 seconds at room temperature. Curve *A*, heated to 309° C.; curve *B*, heated to 266° C.; curve *C*, heated to 207° C.; curve *D*, heated to 153° C.; curve *E*, heated to 98° C.

between the curves in either Fig. 5, 6 or 7 and the coördinate axes ought to be equal to each other. It is impossible to get experimental data with which to draw the curves to the axis so the author projected the curves tentatively. This is not an entirely rash thing to do because a slight variation in the prolongations will affect the areas little; furthermore, while the low intensities were not measurable, one could nevertheless get some idea of the rapidity of decay by noticing how rapidly the photometer screen became dark. Fig. 8 shows the areas plotted with temperatures as abscissæ.

No attempt was made to measure the areas of the curves marked *E* in the figures because the approach to the axis was too slow. If the areas had been equal to each other for a given excitation,

each of the curves in Fig. 8 would have been a straight line parallel to the temperature axis. With the exception of curve *F*, the curves show the same peculiarities but differ widely from straight lines. A plausible explanation of the shape of the curves is this. The curves of thermo-luminescence at the lower temperatures may have been projected too rapidly to the axis. This will account satisfactorily for the relative positions of the first three points in each curve in Fig. 8. The remaining point in each curve corresponds



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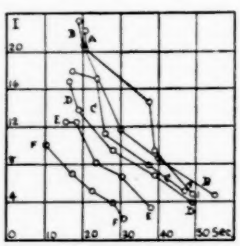

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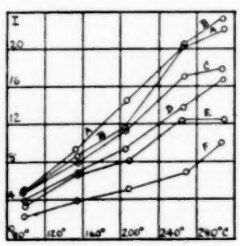


10.

Fig. 8. Areas between the thermo-phosphorescence curves and the coördinate axes. Curve *A*, excited 320 seconds (from Fig. 7); curve *B*, excited 160 seconds; curve *C*, excited 80 seconds (from Fig. 6); curve *D*, excited 40 seconds; curve *E*, excited 20 seconds; curve *F*, excited 10 seconds (from Fig. 5).

Fig. 9. Shifting of the maximum intensity as the temperature is raised. Maximum intensity *vs.* time of maximum intensity measured from the beginning of heating. Curve *A*, excited 320 seconds (from Fig. 7); curve *B*, excited 160 seconds; curve *C*, excited 80 seconds (from Fig. 6); curve *D*, excited 40 seconds; curve *E*, excited 20 seconds; curve *F*, excited 10 seconds (from Fig. 5).

Each point on a curve is for a given temperature. On any curve the lowest point is for 99° C. and for the other points in consecutive order 155°, 207°, 267°, and 308° C., respectively.

Fig. 10. Increase of maximum intensity of thermo-luminescence with increase of temperature. Curve *A*, excited 320 seconds (from Fig. 7); curve *B*, excited 160 seconds; curve *C*, excited 80 seconds (from Fig. 6); curve *D*, excited 40 seconds; curve *E*, excited 20 seconds; curve *F*, excited 10 seconds (from Fig. 5).

to a temperature of about 300° C. At a temperature represented by a very dull red heat, the powder loses temporarily some of its power to phosphoresce and at a higher temperature loses this property permanently. It is possible that at about 300° C. the powder begins to change its character. If these views of the curves in Fig. 8 are correct, then the function of heating (at temperatures between 100° and 300° C.) after excitation is merely to release suddenly energy that was manifesting itself slowly.

If this explanation of the effect of heating is correct, then it would be reasonable to expect that in the case of the curves of Fig. 1 the decay would be more rapid the higher the temperature, which effect has already been pointed out. The effect of greater initial intensity in Fig. 1 with higher temperature during excitation, if one admits that the figure indicates this, may be due to much the same causes as the effect of more rapid decay in the case of higher temperatures, but it may also be due to quite different causes. It is outside the province of this paper to go into this question.

Fig. 9 shows the shifting of the maximum point in the curves of thermo-luminescence as the temperature is raised. No weight is given to the exact shape of the curves, the points being connected merely to aid the eye in distinguishing them. The curves are in accordance with what would be expected if the function of the temperature is to liberate suddenly the phosphorescent energy. If this is the case, the greater the temperature the quicker the energy will be liberated and the brighter the flash. The relation of maximum intensity to temperature is shown more clearly in Fig. 10.

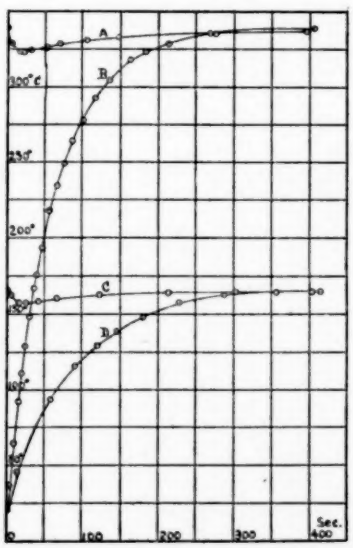


Fig. 11. Curves *A* and *C*, variation in temperature of furnace when the powder is put in. Curves *B* and *D*, increase in temperature of the powder. Curves *A* and *B* do not become identical because they were not taken simultaneously and the temperature changed slightly between the two runs.

The shape of the curves just discussed will depend upon the rate of increase of the temperature of the powder. Two curves were taken in the region of each of the temperatures used to show the increase of temperature of the powder and the variation in temperature of the furnace when the powder is heated. Fig. 11 shows the curves for two of the temperatures. The conclusion drawn from the complete set of curves is that indicated by Fig. 11: the powder reaches a constant temperature in a

constant time independent of the temperature. The periods of the two galvanometers used in the temperature measurements were too short to affect the shape of the curves appreciably.

This method of heating possesses several advantages. The temperatures are known and can be accurately reproduced as many times as desirable. Further, the gradual heating allows the flash to be followed in the photometer. For some other work a strip of platinum which supported a thin layer of the powder was heated by passing an electric current through the strip. The flash in this case occurred too rapidly to be followed, the maximum intensity being the only measurement possible.

It is not easy to estimate the effect of gradual heating as compared with more nearly instantaneous heating. The outside layer

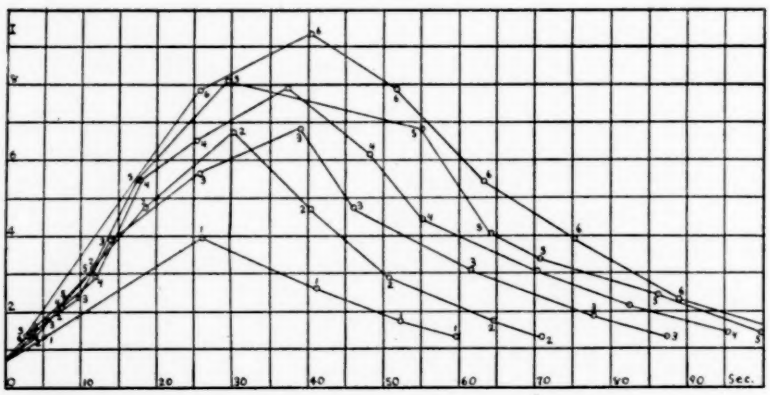


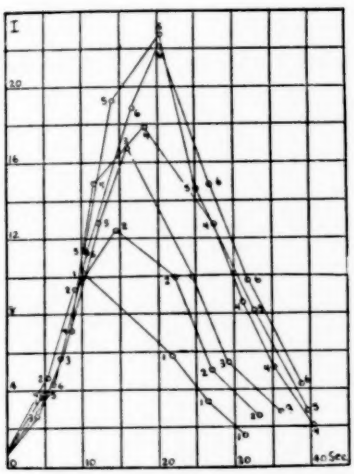
Fig. 12. Effect of varying the length of excitation. The length of excitation and the temperature of the furnace are as follows:

Curve 6, 320.0 sec., 153.0° C.	Curve 3, 40.0 sec., 155.5° C.
" 5, 160.0 " 155.5°	" 2, 19.9 " 155.5°
" 4, 80.1 " 155.5°	" 1, 10.0 " 155.0°

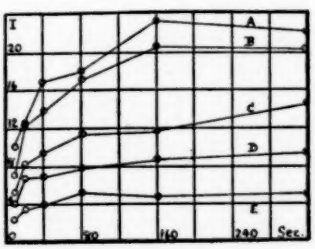
of the powder is subjected to the temperature of the furnace which does not vary widely. It is only the inside layers which are heated as slowly as the curves in Fig. 11 indicate. It is not believed that any material change is introduced in the relation of the various curves, though the actual form of the curves may be changed more or less.

The effect of varying the length of excitation is brought out in Figs. 12 and 13. As in previous curves, the phosphorescence was

excited at room temperature and allowed to decay to $I = 0.8$ before heating. The points are joined by straight lines to aid the eye in following the individual curves. Two effects are noticeable at a glance. The maximum intensity increases with excitation and is shifted to the right, *i. e.*, comes at a later time. The effect of saturation is also shown. This is brought out more clearly in Fig. 14



13.



14.

Fig. 13. Curves similar to Fig. 12. Effect of varying the length of excitation. The length of excitation and the temperature of the furnace are as follows:

Run 6, 320.1 sec., 309 ° C.
" 5, 159.9 " 308°
" 4, 80.2 " 308°
" 3, 39.9 " 308°
" 2, 20.0 " 309°
" 1, 10.0 " 307°

Fig. 14. Saturation effect. I_M *vs.* length of excitation. Curve *A*, temperature 308° C.; curve *B*, temperature 267° C.; curve *C*, temperature 207° C.; curve *D*, temperature 155.5° C.; curve *E*, temperature 98° C.

To get the maximum point in each run, smooth curves, not shown in the figures, were drawn through the different points. These curves show that increasing the excitation beyond a certain length does not increase the energy manifested as thermo-luminescence. That saturation takes place is further shown by the time that luminescence lasts. Figs. 12 and 13 show that the duration of lumi-

nescence has about reached a maximum. The areas included between the curves and the coördinate axes also show that further increase with increased excitation is limited. The shifting of the maximum intensity resembles an inertia effect; the longer the excitation the longer it takes the temperature to produce the maximum thermo-effect.

The effect of delay between the end of excitation and the beginning of heating is shown in Fig. 15.

While Fig. 15 gives a clear idea of the relation of the different curves of thermo-luminescence to the curve of decay of phos-

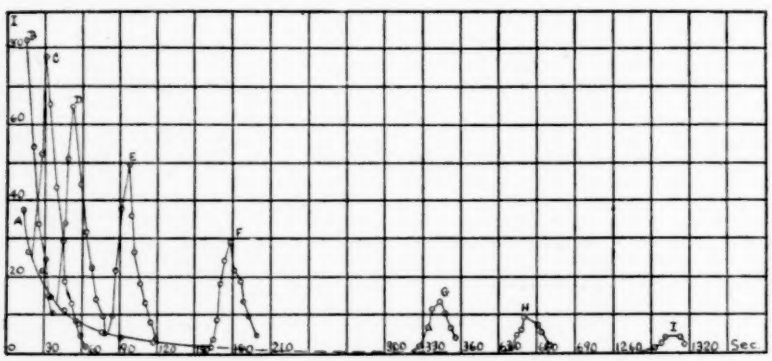


Fig. 15. Effect of delay in heating. Time measured from the end of excitation. Excited 320 seconds at room temperature. Temperature of furnace 303° C. Curve *A*, decay at room temperature. The time between the end of excitation and the beginning of heating is as follows:

Curve *B*,	2.5 sec.	Curve *F*,	162.0 sec.
" *C*,	21.4 "	" *G*,	321.6 "
" *D*,	41.3 "	" *H*,	631.8 "
" *E*,	81.1 "	" *I*,	1280.0 "

phorescence at room temperature, Fig. 16 gives a better idea of the relation between the different curves of thermo-luminescence. Two other sets of these runs under different conditions are given in order that the general characteristics of the curves may be noted.

The last three sets of curves show shifting of the maximum intensity as the delay in heating is increased. The shifting is in the same direction as that noticed in the case of increased length of excitation. The energy of phosphorescence does not manifest itself so rapidly with long delay in heating or long excitation as in the

case of short delay in heating or short excitation. Another point is that at any given excitation and temperature, the curves apparently coincide after a certain time. Out of nine sets of curves, the set in Fig. 16 is the only one that does not exhibit constancy in the time required for the curves of thermo-luminescence to flash out and decay. It is probable that Fig. 16 would show the same

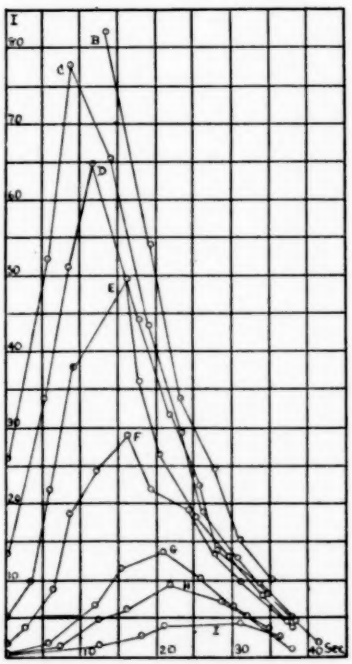


Fig. 16. Effect of delay in heating. Time measured from beginning of heating. Same runs as in Fig. 15.

effect if the curves had been followed to an intensity as low as in the other cases.

Table I. sums up the time for the flash in the case of nine sets of curves gotten under varying conditions. Table I. is naturally very inaccurate because, as seen in Figs. 16, 17 and 18, which are included in the nine sets, the curves do not exactly coincide at any point.

Fig. 19 gives a summary of the nine sets of curves showing the decrease in maximum intensity with delay in heating. Curve *G*, Fig. 19, is taken from Fig. 15.

TABLE I.

Excited	10	sec.	Temp. of furnace			94°	C.	Time for intensity to reach					$I=1.25$	60 sec.
"	10	"	"	"	"	200°		"	"	"	"	"	"	45 "
"	10	"	"	"	"	302°		"	"	"	"	"	"	32 "
"	40	"	"	"	"	92°		"	"	"	"	"	$I=2.5$	100 "
"	40	"	"	"	"	200°		"	"	"	"	"	"	80 "
"	40	"	"	"	"	300°		"	"	"	"	"	"	37 "
"	320	"	"	"	"	93°		"	"	"	"	"	"	120 "
"	320	"	"	"	"	202°		"	"	"	"	"	"	75 "
"	320	"	"	"	"	303°		"	"	"	"	"	"	40? "

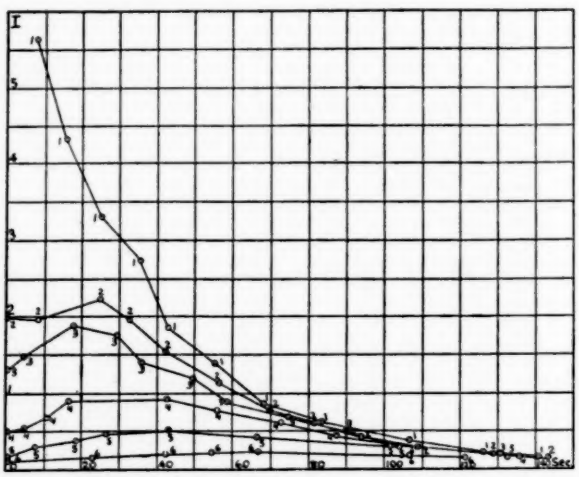


Fig. 17. Effect of delay in heating. Time measured from beginning of heating. Excited 320 seconds at room temperature. Temperature of furnace 93° C. The time between the end of excitation and the beginning of heating is as follows:

Curve 1, 2.0 sec.	Curve 4, 81.5 sec.
" 2, 21.9 "	" 5, 162.0 "
" 3, 41.5 "	" 6, 332.0 "

Fig. 20 shows the maximum intensity in the nine sets of curves plotted against the time of the maximum measured from the beginning of heating. The characteristic shifting of the maximum in the case of delay in heating is clearly seen.

In Fig. 21 is shown the maximum intensity plotted against length of excitation for the nine sets of curves. These curves are similar to those shown in Fig. 14 but cover a larger range of conditions. The straight lines in the figure tend to be misleading for they indicate that the saturation is less complete the shorter the time inter-

vening between excitation and heating. But if one takes Fig. 14 as a model, curves can be drawn through the points in Fig. 21 show-

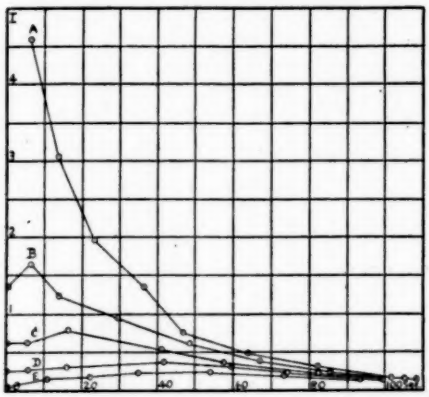


Fig. 18. Curves similar to Fig. 16. Excited 40 seconds at room temperature. Temperature of furnace 94° C. The time between the end of excitation and the beginning of heating is as follows:

Curve *A*, 1.9 sec.
" *B*, 22.1 "
" *C*, 42.1 "
" *D*, 82.6 "
" *E*, 162.1 "

ing that the saturation is probably as complete for one time of delay as another.

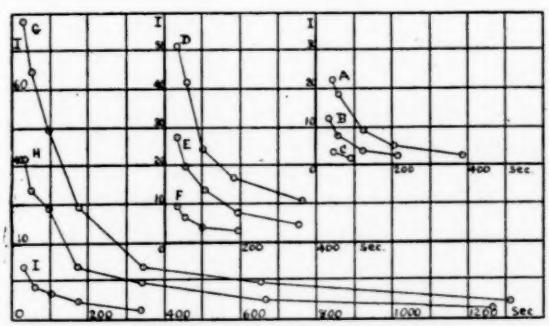


Fig. 19. Decrease in maximum intensity with delay in heating. The coördinates are I_M and time of I_M measured from the end of excitation. The length of excitation and the temperature of the furnace are as follows:

Curve *A*, 320 sec., 93° C.
" *B*, 40 " 92°
" *C*, 10 " 94°
Curve *D*, 320 sec., 202° C.
" *E*, 40 " 200°
" *F*, 10 " 200°
Curve *G*, 320 sec., 303° C.
" *H*, 40 " 300°
" *I*, 10 " 302°

Fig. 22 shows the relation between maximum intensity and temperature for the nine sets of runs. These curves correspond to those shown in Fig. 9. In some of the curves but one point can

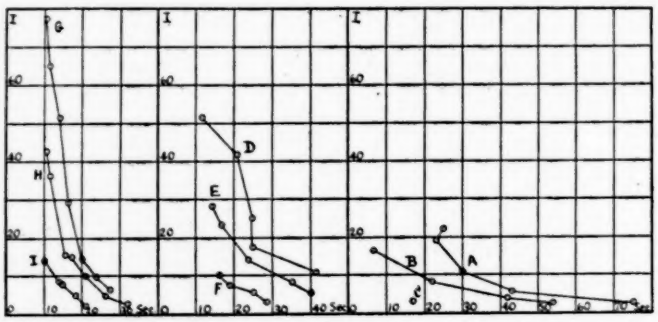


Fig. 20. Maximum intensity *vs.* time of maximum intensity measured from the beginning of heating. For description of curves see Fig. 19.

be given, the other runs showing no measurable intensity or else no maximum. The relation between the maximum intensity and

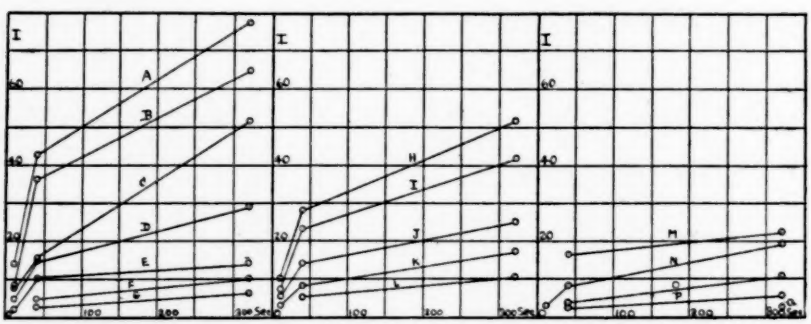


Fig. 21. Maximum intensity *vs.* length of excitation. The temperature of the furnace and the time between the end of excitation and the beginning of heating are as follows:

Curve *A*,	302° C.,	21.6 sec.		Curve *H*,	200° C.,	21.9 sec.	
" *B*,	"	41.7	"	" *I*,	"	41.5	"
" *C*,	"	81.4	"	" *J*,	"	81.6	"
" *D*,	"	161.6	"	" *K*,	"	161.8	"
" *E*,	"	321.0	"	" *L*,	"	321.7	"
" *F*,	"	636.0	"				
" *G*,	"	1155.0	"				

Curve *M*,	93° C.,	21.5 sec.	
" *N*,	"	41.8	"
" *O*,	"	82.0	"
" *P*,	"	162.0	"
" *Q*,	"	322.0	"

the temperature, beyond the fact that the intensity increases with the temperature is not clear.

In many of the figures given, it is probably unwise to lay too much stress upon the exact shape of the curves.

In the first part of this paper mention was made of the existence of two bands in the phosphorescence spectrum of the sample of Sidot blende used in this study when excited by a mercury lamp. If there are two bands, it is natural to expect some indication of their existence in the curves of thermo-luminescence. Referring to Figs. 16

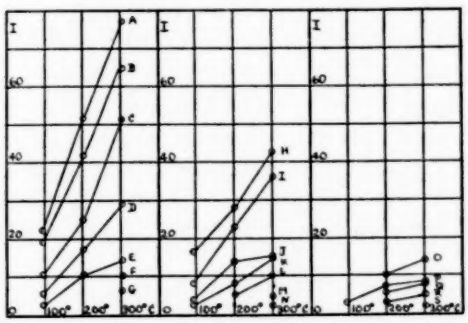


Fig. 22. Maximum intensity *vs.* temperature of furnace. The length of excitation and the time between the end of excitation and the beginning of heating are as follows:

Curve *A*,	320 sec.,	21.7 sec.	Curve *H*,	40 sec.,	22.1 sec.
" *B*,	"	41.3 "	" *I*,	"	41.8 "
" *C*,	"	81.3 "	" *J*,	"	81.6 "
" *D*,	"	162.0 "	" *K*,	"	161.9 "
" *E*,	"	321.8 "	" *L*,	"	321.9 "
" *F*,	"	631.8 "	" *M*,	"	642.0 "
" *G*,	"	1280.0 "	" *N*,	"	1230.0 "

Curve *O*,	10 sec.,	21.8 sec.
" *P*,	"	41.7 "
" *Q*,	"	81.7 "
" *R*,	"	161.4 "
" *S*,	"	319.5 "

and 17, there will be found evidence of two bands. After the intensity has reached a maximum, it falls off rapidly at first, then there is an indication of a slowing up in the decay followed by relatively rapid decay. Whether there is a complete bending back in any of the curves cannot be stated because the points are too far apart. Whether a complete bending back is possible depends on the relative intensities of luminescence of the two bands and the relative

rapidity of decay. It has not seemed advisable to search for more certain indications of two bands in the thermo phosphorescence because of the difficulty of increasing the number of observations taken in a given time. In a paper to follow this, curves will be shown in the case of Balmain's paint, which decays slowly enough to be more completely studied. This substance has two bands in its phosphorescence spectrum and the curves of thermo-luminescence show two maxima under certain conditions of excitation, temperature, and delay in heating. It is possible that the study of this substance has somewhat distorted the author's vision in the case of Sidot blende, but the fact that the indications of a change in the decay of thermo-luminescence correspond in time for the different curves points toward the existence of two bands.

The author wishes to express his obligations to Professor Merritt for suggesting this line of investigation and for other suggestions during the progress of the work.

PHYSICAL LABORATORY OF CORNELL UNIVERSITY.

PROCEEDINGS

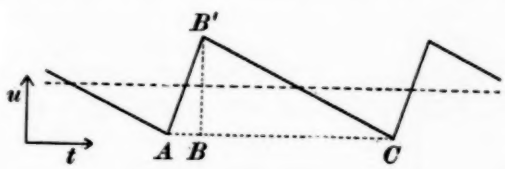
OF THE

AMERICAN PHYSICAL SOCIETY.

HOW DOES A VIOLINIST CONTROL THE LOUDNESS OF HIS TONE?[1]

BY HARVEY N. DAVIS.

ACCORDING to the Helmholtzian theory of the violin string, the motion of the part of the string in contact with the bow can be represented by a simple zigzag line like that in the accompanying figure, if values of the time t are plotted as abscissæ and the corresponding displacements u of the point bowed as ordinates. $B'C$ represents that part of the motion which is in the direction of the bowing, and during it the string is sticking fast to the bow and moving with its velocity. The ratio



of the time-interval BC to the period AC is determined solely by the distance of the point bowed from the ends of the string; if this point is one seventh of the length of the string from the bridge, BC is six sevenths of AC, and so in general. Therefore the amplitude BB' is wholly determined when the position and speed of the bow are given. When the bow is brought nearer the bridge the amplitude BB' increases, and it is easy to prove that the amplitude at the center of the string increases still more, so that the sound should be louder than before. This is indeed the case, as every violinist knows. If, however, it be desirable not to move the bowing point, then, on the Helmholtzian theory, the amplitude of the string and the loudness of the sound produced are wholly determined by the speed of the bow, and are not affected by a change in its pressure — a conclusion that does not seem to be in agreement with experience.

An explanation of this discrepancy can be based on certain results communicated to this Society in a preliminary report a year ago, but not yet published. It was found that to each bowing speed corresponds a certain bowing pressure below which the normal Helmholtzian form

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, December 30, 1907, to January 2, 1908.

cannot be maintained, and that this critical pressure varies very nearly as the bowing speed. It can be considerably exceeded without changing the nature or magnitude of the vibration, but a violinist would ordinarily use as small a pressure as his bowing speed at the moment would allow, both because of the scratching which too great a pressure causes, and to avoid undue fatigue. Therefore, even if loudness is determined by bowing speed alone, a greater bowing speed would always be accompanied by a greater pressure, and this would seem to be the cause of the loud tone. This tends to mask the real issue which is whether loudness increases with pressure at a constant bowing speed; but even when it is allowed for, experience seems to be against the Helmholtzian theory.

The author is therefore led to believe that the actual motion of a violin string is usually not of the normal Helmholtzian type, but of the sort described to the Society a year ago as corresponding to light bowing. It is characteristic of this sub-critical region that diminishing the pressure of the bow carries the ordinary straight line form continuously over into one from which the overtones have entirely disappeared, the amplitude of the fundamental being also somewhat reduced. With the special apparatus previously described to the Society, it is possible, when the string is bowed at its middle point, to reduce the energy of its motion to barely half the normal value, and when the bow is near one end, the reduction is much greater. Since the variations in loudness may, for various reasons, be expected to be even greater than the variations in the energy of the string itself, there should be no difficulty in accounting for the magnitude of the effects actually observed. This explanation obviously requires that the quality of the tone should change when its loudness is varied at constant bowing speed, and this seems to be the case, although the effect is not as marked as might be expected.

The author hopes to be able to determine the limits of the sub-critical region for an actual violin, and to compare with them certain observations already obtained of the pressures ordinarily used. In the meantime he will be grateful for any information which may help either to confirm or to disprove these conclusions.

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THE SPECTRUM OF CALCIUM.[1]

BY JAMES BARNES.

THE paper considers the charges produced in the intensity and distribution of light in the lines of the calcium spectrum obtained from an arc between metallic electrodes in air at atmospheric pressure

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, December 30, 1907, to January 2, 1908.

and at lower pressures with varying current-strength. The results can be explained as a density effect rather than a temperature one.

The new triplets found by Saunders in a copper arc moistened with $CaCl_2$ appear very clearly and sharp when the arc is produced in a vacuum with a current of 12 amperes.

Many attempts were made to obtain true double reversals of the *H* and *K* lines with a steady arc but without success. False multiple and double reversals appear in some of the other lines.

The Resistance Temperature Coefficient and the Coefficient of Expansion of Lampblack.[1]

By G. W. Stewart.

WITH the exception of the diamond and charcoal, carbon in its various forms conducts electricity metallically. Its resistance temperature coefficient is, however, negative. This paper accounts for the apparent negative coefficient by assuming the changes in resistance to be due to the expansion of the particles of carbon.

Assuming this explanation to be the correct one, experiments were performed to obtain the coefficient of expansion of carbon. The carbon used was in the form of films made of commercial lampblack and a lacquer called "zapon L." The apparent resistance temperature coefficient of the films and the effect of the expansion of the hard rubber base upon which the films were placed were measured, and the actual coefficient of expansion of the carbon particles was computed. The result obtained shows the coefficient of carbon in the form of lampblack to be about 0.0002, which is from ten to thirty times that of the pure metals.

A New Method for Determining the Smallest Interval of Time Perceptible by the Ear.[1]

By Bruce V. Hill.

THIS experiment has been tried many times but, having the apparatus described in a previous paper for the measuring of short intervals of time in condenser discharge at hand, the author with Professor J. E. Boodin, of the University of Kansas, thought it of interest to repeat it.

Through the primary of a small induction coil were connected two parallel circuits, each under the control of one of the keys to be liberated by the falling weight. The secondary of the coil was connected through a cable, to a telephone receiver in a distant room, signals being arranged between the subject in this room and the operator of the falling weight

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, December 30, 1907, to January 2, 1908.

apparatus. The parallel resistances were adjusted till the subject was unable to distinguish which of the two circuits was opened.

A series of stimuli were then given, successive and simultaneous impulses being given at random, till the answers of the subject were as often incorrect as correct. Results as low as .00144 second were thus obtained. This discrimination was evidently not of an interval but rather of duration or of a quality difference. The estimate of interval proper is difficult to make, as so much depends upon the candor of the subject. The interval thus found was .007 second, which agrees well with that found by former experimenters.

The secondary of the induction coil was connected to the moving part of an oscillograph, and the beam of light made to fall upon a cylinder covered with a sensitive film and rotated at a high speed by a motor. With an interval of .0015 the oscillograph showed two distinct impulses.

CHICAGO, ILLINOIS,
November 15, 1907.

A RELATION OF MASS TO ENERGY.[1]

BY DANIEL F. COMSTOCK.

IN the paper of which this is an abstract it is shown that the momentum of any purely electric system having any internal motions and constraints, but possessing on the whole a kind of average symmetry, is given by the expression

$$M = \frac{2 W_T v}{V^2\left[1 + \left(\frac{v}{V}\right)^2\right]}.$$

Here M is the momentum of the system, (v) its velocity as a whole, V the velocity of light and W_T the part of the total electromagnetic energy which is represented by the components of the electric and magnetic forces which lie perpendicular to the direction of motion of the system. This is a highly general result and is obtained by a method involving the generalized constraints of the system.

When the second order of the ratio v/V may be neglected, W_T is equal to two thirds the total electromagnetic energy (W) of the system (because of the average symmetry before mentioned), and hence we have

$$\text{Mass} = \frac{4}{3}\frac{1}{V^2} W.$$

This gives the electromagnetic mass of the system in terms of its total energy content.

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, December 30, 1907, to January 2, 1908.

If the electrical theory of matter be accepted this result applies to the mass of any piece of matter and we have the mass proportional to the total contained energy.

It is shown that if this hypothesis is accepted the irregularities which exist in the table of atomic weights are in harmony with the evolutionary theory of the elements.

Also on this basis gravitation must be considered as acting between quantities of confined energy and not between masses in any other sense.

NEW BOOKS.

Das Problem der Schwingungserzeugung mit besonderer Berücksichtigung schneller elektrischer Schwingungen. By Dr. H. Barkhausen. Pp. 113. Leipzig, S. Hirzel, 1907.

This is a timely book on a live topic. The production of undamped electrical oscillations of high frequency is the principal theme of the book, but the author approaches the subject from the broadest theoretical standpoint; first deducing a series of propositions defining the conditions under which it is possible to derive a sustained periodic current from an aperiodic energy-source, and then discussing in systematic order the various means by which these conditions may be met. Each case is considered theoretically and illustrated by some form of actual apparatus which fulfills the prescribed conditions and affords a more or less practical solution of the problem. The treatment is general enough to include such familiar devices as the alternating-current dynamo and the statical influence machine, the former being regarded as a current system in which the variables are self- and mutual induction, the latter illustrating the case of variable capacity. The old problem of the telephone relay enters as another phase of the subject, where a periodic current already existing is to be strengthened by the addition of energy from an outside aperiodic source.

The center of interest, however, is in the discussion of the singing arc, to which a large part of the book is devoted. The three types of oscillation which this apparatus may execute are described with admirable clearness and illustrated by diagrams derived from the author's equations. It is interesting to note how closely these purely theoretical curves agree with the oscillograph records obtained by Blondel under conditions similar to those here assumed.

A final chapter on the various types of mechanical oscillations and their analogy to the corresponding electrical phenomena will greatly assist the reader in grasping the physical meaning of the generalizations by giving a clearer mental picture of the phenomena involved.

The book is particularly welcome at this time when undamped oscillations are the order of the day in wireless telegraphy and telephony, and all sorts of possible and impossible oscillators are appearing. Even to those not especially interested in the subject it is well worth the reading, and the author's clear logic and often original viewpoint are refreshing and full of suggestiveness. No attempt is made to furnish a complete review of the art. The object is rather to correlate and systematize the diverse and scattered contributions to the subject, and in this the author has been eminently successful. Frederick K. Vreeland.